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Inventor(s)	:	**Lutz MAY** **Wolfratshauser Str. 23a** **82578 Geretsried-Gelting** **Germany** **Citizenship: Germany**

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For	:	**POSITION SENSOR DEVICE, A POSITION SENSOR ARRAY, A CONCRETE PROCESSING APPARATUS AND A METHOD FOR DETERMINING A POSITION OF A RECIPROCATING OBJECT**

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Enclosed herewith please find the following:

1. 1 sheet of Title Page and 69 sheets of Specification.
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Date: September 23, 2004

By: ______________________
Oleg F. Kaplun (Reg. No. 45,559)

Fay Kaplun & Marcin, LLP
150 Broadway, Suite 702
New York, NY 10038
Tel: 212-619-6000
Fax: 212-619-0276

[40124/03901]

U.S. PROVISIONAL PATENT APPLICATION

For

POSITION SENSOR DEVICE, A POSITION SENSOR ARRAY, A CONCRETE PROCESSING APPARATUS AND A METHOD FOR DETERMINING A POSITION OF A RECIPROCATING OBJECT

Inventor(s):

Lutz MAY

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Represented by:

FAY KAPLUN & MARCIN, LLP
150 Broadway, Suite 702
New York, NY 10038
(212) 619-6000 (tel)
(212) 619-0276 (fax)
info@FKMiplaw.com

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Name: Oleg F. Kaplun, Reg. No. 45,559

Signature

Application No.
New Application
NCTENGINEERING GMBH

Our Reference
N 7177 / AD

Munich,
23. September 2004

NCTEngineering GmbH
Otto-Hahn-Straße 24, 85521 Ottobrunn, Germany

Position sensor device, a position sensor array, a concrete processing apparatus and a method for determining a position of a reciprocating object

Background of the Invention

Field of the Invention

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Description of the Related Art

For many applications, it is desirable to accurately measure the position of a moving object. For instance, it is highly advantageous to know the position of a reciprocating object to accurately control the reciprocation in an efficient manner.

According to the prior art, an optical marker can be provided on a reciprocating object, and an optical measurement can be performed to estimate the position of the optical marker and thus a position of the reciprocating object. However, under critical circumstances and conditions such as a dirty environment, the optical marker may be covered by a layer of dirt and may become "invisible" for an optical detecting means.

Further, in case that the reciprocating object is located in a dirty environment, an optical marker can be abrased by friction between the reciprocating object and dirt particles.

Such a scenario of critical conditions is present, for instance, in the case of a concrete processing apparatus in which a reciprocating shaft mixes concrete and in which the position of the reciprocating shaft or work cylinder is desired to known to efficiently control the reciprocation cycle.

Alternatively, a mechanical marker, such as an engraving, can be used as a marker to detect the position or velocity of a reciprocating object. However, such an engraving structure may be filled or covered with dirt and is thus not appropriate to be implemented under critical and dirty conditions. A mechanical marker (engravings) may also present a challenge to maintain pneumatic or hydraulic sealing.

Summary of the Invention

It is an object of the present invention to enable an accurate position detection of a reciprocating object capable of being used under critical conditions like a dirty environment.

This object is achieved by providing a position sensor device, a position sensor array, a concrete processing apparatus and a method for determining a position of a reciprocating object according to independent aspects of the invention mentioned in the following.

In the following, different aspects of the invention will be described.

Aspects 1, 27, 33 and 37 are independent aspects of the invention which may be realized with or without any other means. Aspects 2 to 26 relate to preferred embodiments of aspect 1. Aspects 28 to 32 relate to preferred embodiments of aspect 2. Aspects 34 to 36 relate to preferred embodiments of aspect 3.

1. aspect: A position sensor device for determining a position of a reciprocating object, comprising:

at least one magnetically encoded region fixed on a reciprocating object;

at least one magnetic field detector;

a position determining unit;

wherein the magnetic field detector is adapted to detect a signal generated by the magnetically encoded region when the magnetically encoded region reciprocating with the reciprocating object passes a surrounding area of the magnetic field detector;

wherein the position determining unit is adapted to determine a position of a reciprocating object based on the detected magnetic signal.

2. aspect: The position sensor device according to aspect 1,

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wherein the at least one magnetically encoded region is a permanent magnetic region.

3. aspect: The position sensor device according to aspect 1 or 2,
wherein the at least one magnetically encoded region is a longitudinally magnetized region of the reciprocating object.

4. aspect: The position sensor device according to aspect 1 or 2,
wherein the at least one magnetically encoded region is a circumferentially magnetized region of the reciprocating object.

5. aspect: The position sensor device according to any of aspects 1, 2 or 4,
wherein the at least one magnetically encoded region is formed by a first magnetic flow region oriented in a first direction and by a second magnetic flow region oriented in a second direction, wherein the first direction is opposite to the second direction.

6. aspect: The position sensor device according to aspect 5,
wherein, in a cross-sectional view of the reciprocating object, there is the first circular magnetic flow having the first direction and a first radius and the second circular magnetic flow having the second direction and a second radius, wherein the first radius is larger than the second radius.

7. aspect: The position sensor device according to aspect 1 or 2,
wherein the at least one magnetically encoded region is a magnetic element attached to the surface of the reciprocating object.

8. aspect: The position sensor device according to any of aspects 1 to 7,
wherein the at least one magnetic field detector comprises at least one of the group consisting of

a coil having a coil axis oriented essentially parallel to a reciprocating direction of the reciprocating object;

a coil having a coil axis oriented essentially perpendicular to a reciprocating direction of the reciprocating object;

a Hall-effect probe;

a Giant Magnetic Resonance magnetic field sensor; and

a Magnetic Resonance magnetic field sensor.

9. aspect: The position sensor device according to any of aspects 1 to 8, comprising a plurality of magnetically encoded regions fixed on the reciprocating object.

10. aspect: The position sensor device according to aspect 9, wherein the plurality of magnetically encoded regions are arranged on the reciprocating object at constant distances from one another.

11. aspect: The position sensor device according to aspect 9, wherein the plurality of magnetically encoded regions are arranged on the reciprocating object at different distances from one another.

12. aspect: The position sensor device according to aspect 11, wherein the different distances are selected based on a linear function, a logarithmic function or a power function.

13. aspect: The position sensor device according to any of aspects 9 to 12, wherein the plurality of magnetically encoded regions are arranged on the reciprocating object with constant dimensions.

14. aspect: The position sensor device according to any of aspects 9 to 12,

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wherein the plurality of magnetically encoded regions are arranged on the reciprocating object with different dimensions.

15. aspect: The position sensor device according to any of aspects 9 to 14, wherein different magnetically encoded regions are provided of different magnetic materials.

16. aspect: The position sensor device according to any of aspects 9 to 15, wherein different magnetically encoded regions are provided with different values of magnetization.

17. aspect: The position sensor device according to any of aspects 1 to 16, comprising a plurality of magnetic field detectors.

18. aspect: The position sensor device according to any of aspects 1 to 17, wherein the plurality of magnetic field detectors are arranged along the reciprocating object at constant distances from one another.

19. aspect: The position sensor device according to any of aspects 1 to 17, wherein the plurality of magnetic field detector are arranged along the reciprocating object at different distances from one another.

20. aspect: The position sensor device according to aspect 19, wherein the different distances are selected based on a linear function, a logarithmic function or a power function.

21. aspect: The position sensor device according to any of aspects 1 to 20,

comprising a plurality of magnetically encoded regions fixed on the reciprocating object; and

comprising a plurality of magnetic field detectors.

22. aspect: The position sensor device according to aspect 21,
wherein the arrangement of the plurality of magnetically encoded regions along the reciprocating object corresponds to the arrangement of the plurality of magnetic field detectors.

23. aspect: The position sensor device according to aspect 22,
wherein at least a part of the plurality of magnetic field detectors are arranged displaced from an arrangement of a corresponding one of the plurality of magnetically encoded regions arranged along the reciprocating object.

24. aspect: The position sensor device according to any of aspects 1 to 23,
wherein the number of the magnetically encoded regions equals the number of magnetic field detectors.

25. aspect: The position sensor device according to any of aspects 1 to 23,
wherein the number of the magnetically encoded regions differs from the number of magnetic field detectors.

26. aspect: The position sensor device according to any of aspects 1 to 25,
wherein the reciprocating object is a push-pull-rod in a gearbox of a vehicle.

27. aspect: A position sensor array, comprising

a reciprocating object; and

a position sensor device according to any of aspects 1 to 26 for determining a position of the reciprocating object.

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28. aspect: The position sensor array according to aspect 27,
wherein the reciprocating object is a shaft.

29. aspect: The position sensor array according to aspect 27 or 28,
wherein the magnetically encoded region is provided along a part of the length of the reciprocating object.

30. aspect: The position sensor array according to aspect 27 or 28,
wherein the magnetically encoded region is provided along the entire length of the reciprocating object.

31. aspect: The position sensor array according to any of aspects 27 to 29,
wherein the reciprocating object is divided into a plurality of equally spaced segments, each segment comprising one magnetically encoded region, the magnetically encoded regions of the segments being arranged in an asymmetric manner.

32. aspect: The position sensor array according to any of aspects 27 to 31,
further comprising a control unit adapted to control the reciprocation of the reciprocating object based on the position of the reciprocating object which is provided to the control unit by the position sensor device.

33. aspect: A concrete processing apparatus, comprising

a concrete processing chamber;

a reciprocating shaft arranged in the concrete processing chamber adapted to reciprocate to mix concrete; and

a position sensor device according to any of aspects 1 to 27 adapted to determine a position of the reciprocating shaft.

34. aspect: The concrete processing apparatus according to aspect 33, further comprising a control unit adapted to control the reciprocation of the reciprocating shaft based on the position of the reciprocating shaft which is provided to the control unit by the position sensor device.

35. aspect: The concrete processing apparatus according to aspect 33 or 34, further comprising a vehicle on which the concrete processing chamber, the reciprocating shaft and the position sensor device are mounted.

36. aspect: The concrete processing apparatus according to any of aspects 33 to 35,

comprising a further reciprocating shaft arranged in the concrete processing chamber adapted to reciprocate to mix concrete;

wherein the reciprocating shaft and the further reciprocating shaft are operable in a countercyclical manner.

37. aspect: A method for determining a position of a reciprocating object, comprising the steps of

detecting a signal by a magnetic field detector, the signal being generated by a magnetically encoded region fixed on a reciprocating object when the magnetically encoded region reciprocating with the reciprocating object passes a surrounding area of the magnetic field detector;

determining a position of a reciprocating object based on the detected signal.

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In the following, the above mentioned independent aspects of the invention will be described in more detail.

One idea of the invention may be seen in the aspect to enable accurate position detection of a reciprocating object, such as a reciprocating working cylinder of a concrete (or cement) processing apparatus, by providing one or more magnetically encoded regions on the reciprocating object. When the reciprocating object reciprocates, the magnetically encoded region passes – from time to time - an area of sensitivity/a sufficient close vicinity of a magnetic field detector so that a counter electromotive force may be generated in a magnetic coil as a magnetic field detector by which the presence of the magnetically encoded region can be detected. Since the position of the magnetically encoded regions on the reciprocating object is known or can be predetermined, the determining unit can derive from the detected signal the actual position of the reciprocating object. To determine the position of the reciprocating object from the detected signal, correlation information can be taken into account. Such correlation information can be pre-stored in a memory device coupled with the position determining unit and may correlate the presence of a particular signal of a particular magnetically encoded region with a corresponding position of the shaft. In other words, correlation information correlates a detected (electrical) signal with a position of the object.

"Position" in the context of this description particularly means the information that a particular region or point of the reciprocating object is located at a determined position at a particular point of time.

The fact that the magnetically encoded region is fixed on the reciprocating object means that it may be integrated as a part of the object or alternatively may be attached as an external element to the surface of the object.

Particularly, one or more magnetically encoded regions can be formed on different portions of a hydraulic work cylinder, wherein each of magnetic field detector(s) senses a detecting signal each time a magnetically encoded region traverses a sphere of sensitivity of the magnetic field detector. Thus, the position, the velocity, the acceleration, and so on, of the working cylinder can be estimated with high accuracy, wherein this information can be used to drive the cylinder in a controlled manner to optimize its function.

Since the detection principle of the invention is contactless, the detection is not disturbed by friction effects and does not require a dirt-free environment. Thus, the invention particularly may advantageously be applied in technical fields in which a dirty environment may occur, for instance as a position detecting apparatus for a reciprocating shaft in a concrete processing apparatus, in the field of oil boring, and in the field of mining.

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Further, the magnetic position detecting principle of the invention can be manufactured with low effort, is easy to handle and can be applied to any existing shaft by magnetizing a part of the shaft using a method which will described in detail below (PCME, "Pulse-Current-Modulated Encoding"). For instance, many industrial steels used for shafts of an engine or a work cylinder can be magnetized to form a magnetically encoded region of the invention. The detection principle of the invention is very sensitive and provides a good signal to noise ratio. The invention can be applied to reciprocating objects like a reciprocating shaft having a full scale measurement range preferably in the range of 1 millimetre to 1 meter, but which may be less than 1 millimetre, or which may be as much as 1 (or more) meters.

The invention particularly allows to identify certain (absolute) positions (or fix points) on a reciprocating object, like the position where a pump or generator has to be shut off (on-off function). This invention can also be used to make a precise measurement at a specific range on a reciprocating object (defining a linear position on an object).

While different types of linear positioning sensors (the concept of which differ fundamentally from the concept of the invention) exist in large quantities and that for a relative long time, this particular invention is particularly designed to function under harsh and abrasive conditions where most other technologies will fail.

A very important aspect of a PCME based linear position sensing technology according to a preferred embodiment of the invention is that the magnetic pick-up device may be very small and therefore can be easily placed in small spaces, like inside of a sealing chamber in a pneumatic or hydraulic device.

Another benefit is that the magnetic field emanating from the permanent magnetic markers is relatively small and therefore will not attract metallic particles. A typical magnetic proximity sensor (like an automotive wheel-speed sensor) uses very strong magnetic field to function reliable. Therefore ferromagnetic particles will stick on the surface of such sensors which is why they cannot be used in dirty environments.

The technology of the invention may be also used, in the frame of a concrete processing apparatus, to control the hydraulic cylinder position of the crane arm that carries the mixed and still liquid concrete mass through a long and flexible pipe to a specific location at a building site.

The hydraulic cylinders need to be extended or contracted so that the height and position of the crane arm can be changed. The PCME magnetic markers are appropriate to identify the exact position at the cylinder and to detect vibrations or oscillations that are caused by the concrete pump and the pulsing semi-liquid mass in the flexible pipe.

When the crane arm is pulsing/vibrating to much then the pump has to change its operation to prevent a problem (crane arm is moving outside of the acceptable position tolerance).

In the following, preferred embodiments of the position sensor device according to the first independent aspect of the invention will be described. However, these embodiments also apply for the position sensor array, the concrete processing apparatus and the method for determining a position of a reciprocating object according to other independent aspects of the invention.

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The at least one magnetically encoded region of the position sensor device may be a permanent magnetic region. The term “permanent magnetic region” refers to a magnetized material which has a remaining magnetization also in the absence of an external magnetic field. Thus, “permanent magnetic materials include ferromagnetic materials, ferrimagnetic materials, or the like. The material of such a magnetic region may be a 3d-ferromagnetic material like iron, nickel or cobalt, or may be a rare earth material (4f-magnetism).

The at least one magnetically encoded region may be a longitudinally magnetized region of the reciprocating object. Thus, the magnetizing direction of the magnetically encoded region may be oriented along the reciprocating direction of the reciprocating object. A method of manufacturing such a longitudinally magnetized region is disclosed, in a different context, in WO 02/063262 A1, and uses a separate magnetizing coil.

Alternatively, the at least one magnetically encoded region may be a circumferentially magnetized region of the reciprocating object. Such a circumferentially magnetized region may particularly be adapted such that the at least one magnetically encoded region is formed by a first magnetic flow region oriented in a first direction and by a second magnetic flow region oriented in a second direction, wherein the first direction is opposite to the second direction.

Thus, the magnetically encoded region may be realized as two hollow cylinder-like structures which are oriented concentrically, wherein the magnetizing directions of the two

concentrically arranged magnetic flow regions are preferably essentially perpendicular to one another. Such a magnetic structure can be manufactured by the PCME method described below in detail, i.e. by directly applying a magnetizing electrical current to the reciprocating object made of a magnetizable material. To produce the two opposing magnetizing flow portions, current pulses can be applied to the shaft.

Referring to the described embodiment, in a cross-sectional view of the reciprocating object, there may be a first (circular) magnetic flow having the first direction and a first radius and the second (circular) magnetic flow having the second direction and a second radius, wherein the first radius is larger than the second radius.

Alternatively, the at least one magnetically encoded region may be a (separate) magnetic element attached to the surface of the reciprocating object. Thus, an external element can be attached to the surface of the reciprocating object in order to form a magnetically encoded region. Such a magnetic element can be attached to the reciprocating object by adhered it (e.g. using glue), or may alternatively be fixed on the reciprocating shaft using the magnetic forces of the magnetic element.

Instead of attaching a magnetic object to the surface of the reciprocating object, it is also possible to use materials with different magnetic properties (one material has a higher, and the other a lower permeability, for example). The magnetic object can be attached from the outside of the shaft/cylinder or can be placed inside of the cylinder.

When using materials of different permeabilities, then an additional magnetic encoding of the shaft or cylinder is no longer necessary. An external magnetic source can be used (in

conjunction with the magnetic pick-up device) to detect when the magnetic flux is changing as a consequence of the moving shaft.

Any of the magnetic field detectors may comprise a coil having a coil axis oriented essentially parallel to a reciprocating direction of the reciprocating object. Further, any of the magnetic field detectors may be realized by a coil having a coil axis oriented essentially perpendicular to a reciprocating direction of the reciprocating object. A coil being oriented with any other angle between coil axis and reciprocating direction is possible and falls under the scope of the invention. Alternatively to a coil in which the moving magnetically encoded region may induce an induction voltage by modulating the magnetic flow through the coil, a Hall-effect probe may be used as magnetic field detector making use of the Hall effect. Alternatively, a Giant Magnetic Resonance magnetic field sensor or a Magnetic Resonance magnetic field sensor may be used as a magnetic field detector. However, any other magnetic field detector may be used to detect the presence or absence of one of the magnetically encoded regions in a sufficient close vicinity to the respective magnetic field detector.

Preferably, a plurality of magnetically encoded regions may be fixed on the reciprocating object. By providing a plurality of magnetically encoded regions, a number of fixed points on the reciprocating shaft are defined which may be detected separately so that the number of detection signals is increased. Consequently, the sensitivity and the accuracy of the position detection may be improved.

The plurality of magnetically encoded regions may be arranged on the reciprocating object at constant distances from one another. Thus, each time one of the magnetically encoded regions passes one of the magnetic field detectors, the reciprocating object has moved by a distance which equals the distance between the magnetically encoded regions. Thus, the position of the reciprocating shaft can be estimated in a time-dependent manner with high accuracy.

Alternatively, the plurality of magnetically encoded regions may be arranged on the reciprocating object at different distances from one another. For instance, the different distances may be selectively based on a linear function, on a logarithmic function or by a power function (for instance a power of two or of three). Thus, the time between the detection of subsequent signals by one of the magnetic field detectors follows the mathematical function according to which the magnetic encoding regions of the invention are separated from one another. This allows a unique assignment of the present position of the reciprocating object.

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Such a mathematical function can be a positive (increasing) function or a negative (decreasing) function, meaning that the spacing can become larger from one to the next magnetic marker, or it can become smaller from one to the next.

The plurality of magnetically encoded regions may be arranged on the reciprocating object with constant dimensions. A constant dimension (e.g. constant width, constant thickness, etc.) yields signals of a constant length in time as detected by any of the magnetic field detectors. However, in a scenario in which the reciprocating object reciprocates with a non-constant velocity, the length of the signals will change, so that velocity and acceleration information can be determined from the length of the signal in time.

Alternatively, the plurality of magnetically encoded regions may be arranged on the reciprocating object with different dimensions. This, similar to the case of providing the magnetically encoded regions at different distances from one another, allows a unique assignment of the magnetically encoded region which presently passes one of the magnetic field detectors.

Thus, the magnetic markers can be either all of the same physical dimensions (same width) or they can be of different dimensions (like becoming larger one-after-each-other). In the same way the physical dimensions of the markers can be changed, so can be their signal strength. For example: The markers are all of the same physical dimensions and they are all placed one-after-each-other with the same spacing to each other. The difference from one marker to the next is that the signal amplitude (generated by the permanently stored magnetic field, inside the marker) is increasing from one marker to the next.

Different magnetically encoded regions may be provided made of different magnetic materials, and/or may be provided with different values of magnetization. According to this embodiment, the amplitude or strength of the individual detection signals are different for

each of the magnetically encoded regions so that a unique assignment of a detection signal to one of the magnetically encoded regions, being the origin for such a signal, can be carried out.

The position sensor device according to the invention may comprise a plurality of magnetic field detectors. This further allows to refine the detection performance.

The plurality of magnetic field detectors may be arranged along the reciprocating object at constant distances from one another.

Alternatively, the plurality of magnetic field detectors may be arranged along the reciprocating object at different distances from another.

The different distances may be selected based on a linear function, a logarithmic function or a power function.

Such a mathematical function can be a positive (increasing) function or a negative (decreasing) function, meaning that the spacing can become larger from one to the next detector, or it can become smaller from one to the next.

The position sensor device according to the invention may comprise a plurality of magnetically encoded regions fixed on the reciprocating object and may comprise a plurality of magnetic field detectors.

The arrangement of the plurality of magnetically encoded regions along the reciprocating object may correspond to the arrangement of the plurality of magnetic field detectors. In other words, the arrangement of the magnetic encoded regions may be symmetrical and may thus correspond to the arrangement of the magnetic field detectors. In other words, in a reference

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position of the reciprocating object, a central axis of each of the magnetic field detectors may correspond to a central axis of a corresponding one of the magnetically encoded regions.

Alternatively, at least a part of the plurality of magnetic field detectors may be arranged displaced from an arrangement of a corresponding one of the plurality of magnetically encoded regions arranged along the reciprocating object. According to this embodiment, an asymmetric configuration and arrangement of magnetic field detectors with respect to corresponding magnetically encoded regions in a reference state of the reciprocating object is achieved. For example, a first magnetically encoded region may have its central axis aligned in accordance with a central axis of a corresponding magnetic field detector. For a second magnetically encoded region, in the reference state, the central axis may be displaced with respect to a central axis of a corresponding magnetic field detector, and so on. Such a geometric offset may be used to improve the performance of the position sensor device, since the signals occur in a timely shifted manner, thus increasing the amount of detection information and allowing to refine the position determination.

The number of magnetically encoded regions may differ from the number of magnetic field detectors. For example, there may be provided three magnetically encoded regions and four magnetic field detectors. Or, two magnetic field detectors may be provided for each of the magnetically encoded regions. Or, a plurality of magnetic field detectors may be provided for each of the magnetically encoded regions, wherein the number of magnetically field detectors for any of the magnetically encoded regions may differ for different magnetically encoded regions.

In the position sensor device, the reciprocating object can be a push-pull-rod in a gearbox of a vehicle. In an automatic automotive gearbox system, the position of the various tooth-wheels (gear-wheels) may be changed by push-pull-rods. The actual position of such a rod can be measured with the position sensor device.

In the following, preferred embodiments of the position sensor array of the invention will be described. These embodiments apply also for the position sensor device, for the concrete processing apparatus and for the method of determining a position of a reciprocating object.

In the position sensor array, the reciprocating object may be a shaft. Such a shaft can be driven by an engine, and may be, for example, a hydraulically driven work cylinder of a concrete processing apparatus.

The magnetically encoding region may be provided along a part of the length of the reciprocating object. In other words, any of the magnetically encoded regions may extend along a portion of the reciprocating object in longitudinal direction, wherein another portion of the reciprocating object is free of a magnetically encoding region.

Alternatively, the magnetically encoded region may be provided along the entire length of the reciprocating object. According to this embodiment, the whole reciprocating object is magnetized.

The reciprocating object may be divided into a plurality of equally spaced segments, each segment comprising one magnetically encoded region, the magnetically encoded regions of the segments being arranged in an asymmetric manner. For instance, three segments may be provided, wherein the first segment has a magnetically encoded region in the first third of its length, the second segment has a magnetically encoded region in the middle third of its length and the third and last segment has the magnetically encoded region in the last third of its length. Such a configuration gradually increases the spacing between consecutive markers yielding a characteristic signal pattern allowing an accurate estimation of the reciprocating shaft position.

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Further, a control unit may be provided in the position sensor array adapted to control the reciprocation of the reciprocating object based on the determined position of the reciprocating object which is provided to the control unit by the position sensor device. Thus, the output of the position sensor device, namely the present position of the reciprocating object, is provided to the control unit as feedback information. Based on this back coupling, the control unit can adjust a controlling signal for controlling the reciprocation of the reciprocating object to ensure a proper operation of the reciprocating object.

In the following, preferred embodiments of the concrete processing apparatus will be described. These embodiments also apply to the position sensor device, the position sensor array and the method for determining a position of a reciprocating object.

In a concrete processing apparatus, a control unit may be provided adapted to control the reciprocation of the reciprocating shaft based on the position of the reciprocating shaft which is provided to the control unit by the position sensor device.

The concrete processing apparatus may further comprise a vehicle on which the concrete processing chamber, the reciprocating shaft and the position sensor device may be mounted. Thus, a mobile concrete processing apparatus provided on a vehicle is created which can be flexibly transported to a place of installation.

The concrete processing apparatus of the invention may further comprise a further reciprocation shaft arranged in the concrete processing chamber adapted to reciprocate to mix concrete material. The reciprocating shaft and the further reciprocating shaft are operable in a countercyclical manner. In other words, two reciprocating shafts or cylinders may be provided to mix concrete material, wherein the two reciprocating shafts move in opposite directions in each operation state. For instance, in a scenario in which the first reciprocation shaft moves in a forward direction, the second reciprocation shaft moves in the backwards

direction, and vice versa. By taking this measure, an excellent mixture of the concrete in the concrete processing apparatus is achieved. In order to accurately control the mixing of the concrete by the two reciprocating shafts, it is necessary to control the motion of the reciprocating shafts on the basis of estimated position information generated by the position sensor device. Particularly, in an operation state of the reciprocating shafts, in which they change their motion direction, it is particularly important to control the operation of the reciprocating shafts, since the energy consumption in this state is particularly high.

In the following, further aspects of the invention will be described which fall under the scope of the invention.

An amplitude, an algebraic sign, and/or a slope of a detected signal can be used to derive direction information, i.e. to determine if the reciprocating object moves from a first direction to a second direction or from the second direction to the first direction. According to the invention, one signal or a plurality of signals may be analyzed/evaluated to allow an unambiguous assignment of the detection signals to a position of the reciprocating object to be detected. The arrangement of the magnetic field detectors and of the magnetically encoded regions is preferably selected such that a signal sequence of the magnetic field detectors is unique with respect to a particular position of the reciprocating object.

The magnetic position detection principle of the invention, in contrast to optical or mechanical marker detection methods, is abrasion free and operates without errors even in a scenario in which critical conditions (like concrete powder or other kind of dirt) are present.

Further, the magnetic position detection principle of the invention can be used in a wide temperature range. The only physical restriction concerning the temperature range in which the magnetic detection principle of the invention may be implemented is the Currie temperature of the used magnetic material. Thus, the magnetic components of the system of

the invention can be used – with a reciprocating object made of industrial steel – up to 400°C and more. A limiting factor for the maximum operation temperature of the system of the invention may be the temperature up to which an isolation of a coil as a magnetic field detector keeps intact. However, with available coils, a temperature of at least 210°C can be obtained. Thus, the system of the invention is very temperature stable. Since the detection principle of the invention is contactless, a cooling element can be provided in an environment in which very high temperatures are present. Such a cooling element can be a water cooling element, for instance.

The lengths of a reciprocating shaft for an implementation in a concrete processing apparatus may be 5 meters and more.

In principle, using one magnetic field detector, for instance one coil, is sufficient. However, in order to eliminate the influence of the magnetic field of the earth, two detection coils may be used with oppositely oriented coil axis, so that the influence of the earth magnetic field can be eliminated by considering the two signals of the two coils. The detection of the position can include counting the number of markers which pass one or more magnetic field detectors per time.

The above and other aspects, objects, features and advantages of the present invention will become apparent from the following description and the appended claim, taken in conjunction with the accompanying drawings in which like parts or elements are denoted by like reference numbers.

Brief Description of the Drawings

The accompanying drawings, which are included to provide a further understanding of the invention and constitute a part of the specification illustrate embodiments of the invention.

In the drawings:

Fig.1 shows a position sensor array according to a first embodiment of the invention.

Fig.2 shows a position sensor array according to a second embodiment of the invention.

Fig.3 shows a position sensor array according to a third embodiment of the invention.

Fig.4 shows a position sensor array according to a forth embodiment of the invention.

Fig.5 shows a position sensor array according to a fifth embodiment of the invention.

Fig.6 shows a diagram illustrating a detection signal as detected by the magnet field detection coil of the position sensor array according to the forth embodiment of the invention.

Fig.7 shows a position sensor array according to a sixth embodiment of the invention.

Fig.8 shows a diagram illustrating a detection signal as detected by the magnet field detection coil of the position sensor array according to the sixth embodiment of the invention.

Fig.9 shows a position sensor array according to a seventh embodiment of the invention.

Fig.10 shows a concrete processing apparatus according to a first embodiment of the invention.

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Fig.11 shows a concrete processing apparatus according to a second embodiment of the invention.

Fig.12 to **Fig.67** illustrate the PCME technology which, according to the invention, is preferably used to form at least one magnetically encoding region on at least part of a reciprocating shaft.

Fig.68 and **Fig.69** show schematic views illustrating a sequence of signals captured by three magnetic field detectors generated by six magnetic encoded regions provided on a reciprocating shaft of a position sensor array according to an eighth embodiment of the invention.

Fig.70 and **Fig.71** show schematic views illustrating a sequence of signals captured by two magnetic field detectors generated by six magnetic encoded regions provided on a reciprocating shaft of a position sensor array according to a ninth embodiment of the invention.

Fig.72 shows a schematic view illustrating a sequence of signals captured by one magnetic field detector generated by six magnetic encoded regions provided on a reciprocating shaft of a position sensor array according to a tenth embodiment of the invention.

Fig.73 to **Fig.75** show hollow tubes as reciprocating objects with different embodiments for magnetic encoded regions arranged inside the hollow tube.

Fig.76, **Fig.77** show a position sensor array according to an eleventh embodiment of the invention.

Detailed Description of Preferred Embodiments of the Invention

In the following, referring to **Fig.1**, a position sensor array 100 according to a first embodiment of the invention will be described.

The position sensor array 100 comprises a reciprocating shaft 101 driven by a motor (not shown in Fig.1), wherein the reciprocating shaft 101 reciprocates along a reciprocation direction 102. Further, the position sensor array 100 comprises a position sensor device for determining a position of the reciprocating shaft 101. The position sensor device for determining a position of the reciprocating shaft 101 comprises one magnetically encoded region 103 integrated in a surface region of the reciprocating shaft 101. Further, the position sensor device comprises one detection coil 104, a measuring unit 105 for measuring a magnetic field based on the electrical signals provided by the detection coil 104, and a determining unit 106. The detection coil 104 is adapted to detect a signal generated by the magnetically encoded region 103 when the magnetically encoded region 103 reciprocating with the reciprocating shaft 101 passes a surrounding area of the detection coil 104. In this surrounding area, a present magnetic element can be detected by the detection coil 104. The determining unit 106 is adapted to determine the position of the reciprocating shaft 101 based on the detected signal, which is measured by a measuring unit 105 coupled with the detection coil 104.

The magnetically encoded region 103 is realized according to the PCME technology described below. Therefore, the magnetically encoded region 103 is a permanent magnetic region having a circumferentially magnetized region of the reciprocating shaft 101 made from industrial steel. The magnetically encoded region 103 is formed by a first magnetic flow region oriented in a first direction and by a second magnetic flow region oriented in a second direction, wherein the first direction is opposite to the second direction. In a cross-sectional view of the cylindrical reciprocating shaft 101 perpendicular to the paper plane of Fig.1 and

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perpendicular to the reciprocating direction 102 of the reciprocating shaft 101, there is a first circular magnetic flow having the first direction and a first radius and the second circular magnetic flow having the second direction and a second radius, wherein the first radius is larger than the second radius.

When the reciprocating shaft 101, driven by an engine which is not shown in Fig.1, reciprocates along the reciprocation direction 102, i.e. oscillates along a direction 102 from left to right and vice versa, the magnetic flux through the detection coil 104 generated by the magnetically encoded region 103 varies with the time, since the magnetically encoded region 103 has a time dependent distance from the detection coil 104. Thus, depending on the actual position of the reciprocating shaft 101, the induced voltage in the detection coil 104 yielding a signal in the measuring unit 105, varies dependent of the actual position of the reciprocating shaft 101. Based on this measured signal, the determining unit 106 determines the actual position of the reciprocating shaft. The determining unit 106 provides this position information to the control unit 107 which uses this information to regulate control signals for controlling the reciprocation of the reciprocating shaft 101.

In the following, referring to **Fig.2**, a position sensor array 200 according to a second embodiment of the invention will be described.

In contrast to the position sensor array 100, the position sensor array 200 comprises a plurality of magnetically encoded regions divided in a first group 201 of magnetically encoded regions and a second group 202 of magnetically encoded regions which are provided at different locations on the reciprocating shaft 101. Instead of the detection coil 104, the position sensor array 200 comprises a first Hall-probe 203, a second Hall-probe 204 and third Hall-probe 205 arranged along the reciprocating shaft 101. When the reciprocating shaft 101 reciprocates along a reciprocation direction 102, the plurality of magnetically encoded regions 201, 202 pass the Hall-probes 203 to 205 to produce a significant and unique time dependent

signal pattern detected by the Hall-probes 203 to 205 and measured by the measuring unit 105, so that the determining unit 106 can calculate the position of the reciprocating shaft 101 based on the sequence of signals.

Thus, the position sensor array 200 allows to sense the actual position of the reciprocating shaft 101 on the basis of the PCME technology in cascading sequence. The PCME encoding field group 201, 202 magnetically encoded regions have a different length along the reciprocation direction 102, whereby on one side of the reciprocating shaft 101 the shorter PCME encoding region 201 is placed and at the other end of the shaft 101 is the wider PCME encoding region 202.

The reciprocating shaft 101 is a hydraulic work cylinder. As can be seen from Fig.2, the short magnetic position markers 201 are cascaded, and the long magnetic position markers 202 are cascaded.

In the following, referring to **Fig.3**, a position sensor array 300 according to a third embodiment of the invention will be described.

The position sensor array 300 differs from the position sensor array 100 in that a plurality of equal-width magnetically encoded regions 301 are provided. Each of the magnetically encoded regions 301 has an equal width, l, along the reciprocating shaft 101. The magnetically encoded regions 301 are provided at different distances from one another, namely a distances of d, 2d, and 3d. In contrast to the horizontally aligned detection coil 104 of Fig.1, Fig.3 shows a plurality of vertically aligned detection coils 302 having their coil axis arranged vertically according to the drawing of Fig.3. The different distances between adjacent magnetically encoded regions and adjacent detection coils 302 yield a time dependent pattern of signals generated in the detection coils 302 which allow to retrieve the actual position and velocity of the reciprocating shaft 101.

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The arrangement of the coils 302 with respect to the magnetically encoded regions 301 is symmetric, i.e. in a reference state of the reciprocating shaft 101 shown in Fig.3, a central axis of each of the coils 302 equals to a central axis of a corresponding one of the magnetically encoded regions 301.

In the following, referring to **Fig.4**, a position sensor array 400 according to a fourth embodiment of the invention will be described.

In the case of the position sensor array 400, a single horizontally aligned detection coil 104 is provided, and three equal-width magnetically encoded regions 301. When the shaft 101 reciprocates along direction 102, a detection signal is detected by the horizontally aligned detection coil 104 each time that one of the equal-width magnetically encoded regions 301 passes a close vicinity of the horizontally aligned detection coil 104. Thus, a sequence of signals is detected at the detection coil 104 which allows to recalculate the actual position of the shaft 101.

In the following, referring to **Fig.5**, a position sensor array 500 according to a fifth embodiment of the invention will be described.

The position sensor array 500 includes two ferromagnetic rings 501 attached on different portions of the reciprocating shaft 101. These ferromagnetic rings 501 made of iron material are separate ferromagnetic elements which are attached on the reciprocating shaft 101 to form magnetically encoded regions. Further, two horizontally aligned detection coils 104 are provided to measure a time dependent magnetic field via an induction voltage which is generated in a respective one of the coils 104 when one of the ferromagnetic rings 501 passes one of the horizontally aligned detection coils 104. As can be seen from the reference position of the reciprocating shaft 101 shown in Fig.5, the ferromagnetic rings 501 are provided at positions of the shaft 101 which are non-symmetric with respect to the detection coils 104. In

other words, in a configuration in which the position of the detection coil 104 shown on the left hand side of Fig.5 corresponds to the position of the ferromagnetic ring 501 shown on the left hand side of Fig.5, there is an offset between the position of the centre of the detecting coil 104 shown on the right hand side of Fig.5 and the position of the central axis of the ferromagnetic ring 501 shown on the right hand side of Fig.5. Consequently, the detection signals of the different coils 104 are timely shifted with respect to each other. Such a time offset yields further position information of the reciprocating shaft 101.

Referring to **Fig.6**, a diagram 600 will be described showing a signal curve 603 which can be detected by the coils 104 shown in Fig.4 when one of the magnetically encoded regions 301 passes the respective coil 104. Along an abscissa 601 of diagram 600, the position x of the reciprocating shaft 101 is shown, and along an ordinate 602, a signal amplitude A(x) is shown. Thus, the signal curve 603 allows to determine the position of the reciprocating shaft 101.

In the following, referring to **Fig.7**, a position sensor array 700 according to a sixth embodiment of the invention will be described. In contrast to the position sensor array 100, the position sensor array 700 shows an entirely magnetized shaft 701, i.e. a shaft which is entirely made of ferromagnetic material or a shaft which is magnetized along its entire length according to the PCME technology.

Fig.8 shows a diagram 800 having an abscissa 801 along which the position x of the entirely magnetized shaft 701 having a total length L is shown. Along an ordinate 802 of diagram 800, the amplitude A(x) of a signal detected by the determining unit 106 is shown. Thus, the signal of Fig.8 allows a unique identification of the actual position of the entirely magnetized shaft 701 of Fig.7.

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In the following, referring to **Fig.9**, a position sensor array 900 according to a seventh embodiment of the invention will be described.

In the case of the position sensor array 900, the reciprocating shaft 101 is divided into a plurality of equally spaced first to fourth segments 901 to 904. Each segment 901 to 904 comprises one magnetically encoded region 301, the magnetically encoded regions 301 being arranged in an asymmetric manner along the segments 901 to 904. The magnetically encoded region 301 of the first segment 901 is arranged in the very left part, the magnetically encoded region 301 of the second segment 902 is arranged in the middle-left part, the magnetically encoded region 301 of the third segment 903 is arranged in the middle-right part and the magnetically encoded region 301 of the fourth segment 904 is arranged at the very right part of the respective segment. Thus, the arrangement of the magnetically encoded regions 301 is shifted from segment to segment 901 to 904. This yields a unique signal pattern detectable by the coils 302 which allows an accurate estimation of the actual position of the shaft 101.

The equally spaced segments 901, 904 with different locations of the markers 301 allow an estimation of the position of the reciprocating shaft 101 by evaluating the signals detected by the coils 302.

In the following, referring to **Fig.10**, a concrete processing apparatus 1000 according to a first embodiment of the invention will be described.

The concrete processing apparatus 1000 is provided on a truck (not shown) equipped with a concrete mixer pump for mixing concrete material using a reciprocating shaft having the magnetic encoding of the invention. Thus, a concrete pump is equipped with a hydraulically driven work cylinder, i.e. a reciprocating shaft. In order to securely control the function of the reciprocating shaft, the position of the shaft should be known exactly. The invention provides

a method of determining the exact position of the reciprocating cylinder of the concrete processing apparatus 1000.

Fig.10 shows the concrete processing apparatus 1000 having a concrete processing chamber 1001 which includes an inlet 1003 for supplying concrete material 1005 in the concrete processing chamber 1001. A reciprocating work cylinder 1002 mixes the concrete material 1005 by reciprocating along a reciprocation direction 102 and transports the concrete material 1005 to a concrete outlet 1004 connected to a pipeline (not shown) via which the concrete is supplied to a concrete consumer.

The reciprocating work cylinder 1002 has, on its reciprocating shaft, three magnetically encoded regions 301 manufactured according to the PCME technology. Sealing elements 1007 are provided to prevent an undesired mixture of concrete material 1005 with a hydraulic fluid 1006 provided to drive the reciprocating work cylinder 1002. When the magnetically encoded regions 301 pass a detection coil 104, an induction voltage is generated in the coil 104 which is supplied to the measuring unit 105 and which allows the determining unit 106 to estimate the present position of the reciprocating work cylinder 1002. A position indicating signal, in which the actual position of the cylinder 1002 is encoded, is provided to a control unit 107 which uses the position information to optimize a driving control signal to drive the reciprocating work cylinder 1002.

Thus, the invention improves the quality of the generated concrete 1005 and the operation of the reciprocating work cylinder 1002, by enabling an improved way of driving the work cylinder 1002 based on position information of the cylinder 1002.

In the following, referring to **Fig.11**, a concrete processing apparatus 1100 according to a second embodiment of the invention will be described.

Fig.11 shows a twin cylinder pump arrangement having a first working cylinder 1002 and a second work cylinder 1102 which allows a combination of steady and gentle pumping patterns. Hydraulic oil 1006 is pumped under pressure to the working cylinders 1002, 1102. At one time, one of the working cylinders 1002, 1102 extends, while the other one retracts at the same time. Thus, one cylinder 1002, 1102 pumps and draws in concrete material 1005, and the other cylinder 1102, 1002 pumps concrete material 1005 into a connected pipeline (not shown). The assembly of Fig.11 is mounted on a truck to form a machine which is applicable in the construction and civil engineering fields.

In contrast to the concrete processing apparatus 1000, two instead of one work cylinders 1002, 1102 are provided in the case of the concrete processing apparatus 1100, namely the reciprocating work cylinder 1002 and a further reciprocating work cylinder 1102. Moreover, a further concrete inlet 1101 for supplying concrete material in a symmetric manner is provided. Both of the reciprocating work cylinders 1002, 1102 are hydraulically driven using the hydraulic fluid 1006.

According to the operation mode shown in Fig.11, the reciprocating work cylinder 1002 moves along a first direction 1103, whereas the further reciprocating work cylinder 1102 moves along a second direction 1104 which is opposite to the first direction 1103. A separation wall 1105 separates the reciprocating work cylinders 1002, 1102 from each other. Along the shaft of each of the reciprocating cylinders 1002, 1102, a plurality of magnetic encoded regions 301 are provided which produce magnetic signals on coils 104. Each reciprocating cylinder 1002, 1102 has assigned a pair of coils 104 having opposed coil axis, so that an evaluation of the signals generated in the coils 104 of each pair of coils allow to eliminate the influence of the magnetic field of the earth to further improve the accuracy of the detected positions.

In the following, the so-called PCME ("Pulse-Current-Modulated Encoding") Sensing Technology will be described in detail, which can, according to a preferred embodiment of the invention, be implemented to form a magnetically encoded region and to detect a position information of a reciprocating object. In the following, the PCME technology will partly described in the context of torque sensing. However, according to the invention, this concept is implemented in the context of the position sensing of the invention.

In this description, there are a number of acronyms used as otherwise some explanations and descriptions may be difficult to read. While the acronyms "ASIC", "IC", and "PCB" are already market standard definitions, there are many terms that are particularly related to the magnetostriction based NCT sensing technology. It should be noted that in this description, when there is a reference to NCT technology or to PCME, it is referred to exemplary embodiments of the present invention.

Table 1 shows a list of abbreviations used in the following description of the PCME technology.

Acronym	Description	Category
ASIC	Application Specific IC	Electronics
DF	Dual Field	Primary Sensor
EMF	Earth Magnetic Field	Test Criteria
FS	Full Scale	Test Criteria
Hot-Spotting	Sensitivity to nearby Ferro magnetic material	Specification
IC	Integrated Circuit	Electronics
MFS	Magnetic Field Sensor	Sensor Component
NCT	Non Contact Torque	Technology
PCB	Printed Circuit Board	Electronics
PCME	Pulse Current Modulated Encoding	Technology

POC	Proof-of-Concept	
RSU	Rotational Signal Uniformity	Specification
SCSP	Signal Conditioning & Signal Processing	Electronics
SF	Single Field	Primary Sensor
SH	Sensor Host	Primary Sensor
SPHC	Shaft Processing Holding Clamp	Processing Tool
SSU	Secondary Sensor Unit	Sensor Component

Table 1: List of abbreviations

The magnetic principle based mechanical-stress sensing technology allows to design and to produce a wide range of "physical-parameter-sensors" (like Force Sensing, Torque Sensing, and Material Diagnostic Analysis) that can be applied where Ferro-Magnetic materials are used. The most common technologies used to build "magnetic-principle-based" sensors are: Inductive differential displacement measurement (requires torsion shaft), measuring the changes of the materials permeability, and measuring the magnetostriction effects.

Over the last 20 years a number of different companies have developed their own and very specific solution in how to design and how to produce a magnetic principle based torque sensor (i.e. ABB, FAST, Frauenhofer Institute, FT, Kubota, MDI, NCTE, RM, Siemens, and others). These technologies are at various development stages and differ in "how-it-works", the achievable performance, the systems reliability, and the manufacturing / system cost.

Some of these technologies require that mechanical changes are made to the shaft where torque should be measured (chevrons), or rely on the mechanical torsion effect (require a long shaft that twists under torque), or that something will be attached to the shaft itself (press-fitting a ring of certain properties to the shaft surface,), or coating of the shaft surface with a

special substance. No-one has yet mastered a high-volume manufacturing process that can be applied to (almost) any shaft size, achieving tight performance tolerances, and is not based on already existing technology patents.

In the following, a magnetostriction principle based Non-Contact-Torque (NCT) Sensing Technology is described that offers to the user a whole host of new features and improved performances, previously not available. This technology enables the realization of a fully-integrated (small in space), real-time (high signal bandwidth) torque measurement, which is reliable and can be produced at an affordable cost, at any desired quantities. This technology is called: PCME (for Pulse-Current-Modulated Encoding) or Magnetostriction Transversal Torque Sensor.

The PCME technology can be applied to the shaft without making any mechanical changes to the shaft, or without attaching anything to the shaft. Most important, the PCME technology can be applied to any shaft diameter (most other technologies have here a limitation) and does not need to rotate / spin the shaft during the encoding process (very simple and low-cost manufacturing process) which makes this technology very applicable for high-volume application.

In the following, a Magnetic Field Structure (Sensor Principle) will be described.

The sensor life-time depends on a “closed-loop” magnetic field design. The PCME technology is based on two magnetic field structures, stored above each other, and running in opposite directions. When no torque stress or motion stress is applied to the shaft (also called

Sensor Host, or SH) then the SH will act magnetically neutral (no magnetic field can be sensed at the outside of the SH).

Fig.12 shows that two magnetic fields are stored in the SH and running in endless circles. The outer field runs in one direction, while the inner field runs in the opposite direction.

Fig.13 illustrates that the PCME sensing technology uses two Counter-Circular magnetic field loops that are stored on top of each other (Picky-Back mode).

When mechanical stress (like reciprocation motion or torque) is applied at both ends of the PCME magnetized SH (Sensor Host, or Shaft) then the magnetic flux lines of both magnetic structures (or loops) will tilt in proportion to the applied torque.

As illustrated in **Fig.14**, when no mechanical stresses are applied to the SH the magnetic flux lines are running in its original path. When mechanical stresses are applied the magnetic flux lines tilt in proportion to the applied stress (like linear motion or torque).

Depending on the applied torque direction (clockwise or anti-clockwise, in relation to the SH) the magnetic flux lines will either tilt to the right or tilt to the left. Where the magnetic flux lines reach the boundary of the magnetically encoded region, the magnetic flux lines from the upper layer will join-up with the magnetic flux lines from the lower layer and visa-versa. This will then form a perfectly controlled toroidal shape.

The benefits of such a magnetic structure are:

- ☐ Reduced (almost eliminated) parasitic magnetic field structures when mechanical stress is applied to the SH (this will result in better RSU performances).
- ☐ Higher Sensor-Output Signal-Slope as there are two "active" layers that compliment each other when generating a mechanical stress related signal. Explanation: When

using a single-layer sensor design, the "tilted" magnetic flux lines that exit at the encoding region boundary have to create a "return passage" from one boundary side to the other. This effort effects how much signal is available to be sensed and measured outside of the SH with the secondary sensor unit.

- ☐ There are almost no limitations on the SH (shaft) dimensions where the PCME technology will be applied to. The dual layered magnetic field structure can be adapted to any solid or hollow shaft dimensions.
- ☐ The physical dimensions and sensor performances are in a very wide range programmable and therefore can be tailored to the targeted application.
- ☐ This sensor design allows to measure mechanical stresses coming from all three dimensions axis, including in-line forces applied to the shaft (applicable as a load-cell). Explanation: Earlier magnetostriction sensor designs (for example from FAST Technology) have been limited to be sensitive in 2 dimensional axis only, and could not measure in-line forces.

Referring to **Fig.15**, when torque is applied to the SH, the magnetic flux lines from both Counter-Circular magnetic loops are connecting to each other at the sensor region boundaries.

When mechanical torque stress is applied to the SH then the magnetic field will no longer run around in circles but tilt slightly in proportion to the applied torque stress. This will cause the magnetic field lines from one layer to connect to the magnetic field lines in the other layer, and with this form a toroidal shape.

Referring to **Fig.16**, an exaggerated presentation is shown of how the magnetic flux line will form an angled toroidal structure when high levels of torque are applied to the SH.

In the following, features and benefits of the PCM-Encoding (PCME) Process will be described.

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The magnetostriction NCT sensing technology from NCTE according to the present invention offers high performance sensing features like:

- ☐ No mechanical changes required on the Sensor Host (already existing shafts can be used as they are)
- ☐ Nothing has to be attached to the Sensor Host (therefore nothing can fall off or change over the shaft-lifetime = high MTBF)
- ☐ During measurement the SH can rotate, reciprocate or move at any desired speed (no limitations on rpm)
- ☐ Very good RSU (Rotational Signal Uniformity) performances
- ☐ Excellent measurement linearity (up to 0.01% of FS)
- ☐ High measurement repeatability
- ☐ Very high signal resolution (better than 14 bit)
- ☐ Very high signal bandwidth (better than 10 kHz)

Depending on the chosen type of magnetostriction sensing technology, and the chosen physical sensor design, the mechanical power transmitting shaft (also called "Sensor Host" or in short "SH") can be used "as is" without making any mechanical changes to it or without attaching anything to the shaft. This is then called a "true" Non-Contact-Torque measurement principle allowing the shaft to rotate freely at any desired speed in both directions.

The here described PCM-Encoding (PCME) manufacturing process according to an exemplary embodiment of the present invention provides additional features no other magnetostriction technology can offer (Uniqueness of this technology):

- ☐ More then three times signal strength in comparison to alternative magnetostriction encoding processes (like the "RS" process from FAST).
- ☐ Easy and simple shaft loading process (high manufacturing through-putt).

- ☐ No moving components during magnetic encoding process (low complexity manufacturing equipment = high MTBF, and lower cost).
- ☐ Process allows NCT sensor to be "fine-tuning" to achieve target accuracy of a fraction of one percent.
- ☐ Manufacturing process allows shaft "pre-processing" and "post-processing" in the same process cycle (high manufacturing through-putt).
- ☐ Sensing technology and manufacturing process is ratio-metric and therefore is applicable to all shaft or tube diameters.
- ☐ The PCM-Encoding process can be applied while the SH is already assembled (depending on accessibility) (maintenance friendly).
- ☐ Final sensor is insensitive to axial shaft movements (the actual allowable axial shaft movement depends on the physical "length" of the magnetically encoded region).
- ☐ Magnetically encoded SH remains neutral and has little to non magnetic field when no forces (like torque) are applied to the SH.
- ☐ Sensitive to mechanical forces in all three dimensional axis.

In the following, the Magnetic Flux Distribution in the SH will be described.

The PCME processing technology is based on using electrical currents, passing through the SH (Sensor Host or Shaft) to achieve the desired, permanent magnetic encoding of the Ferro-magnetic material. To achieve the desired sensor performance and features a very specific and well controlled electrical current is required. Early experiments that used DC currents failed because of luck of understanding how small amounts and large amounts of DC electric current are travelling through a conductor (in this case the "conductor" is the mechanical power transmitting shaft, also called Sensor Host or in short "SH").

Referring to **Fig.17**, an assumed electrical current density in a conductor is illustrated.

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It is widely assumed that the electric current density in a conductor is evenly distributed over the entire cross-section of the conductor when an electric current (DC) passes through the conductor.

Referring to **Fig.18**, a small electrical current forming magnetic field that ties current path in a conductor is shown.

It is our experience that when a small amount of electrical current (DC) is passing through the conductor that the current density is highest at the centre of the conductor. The two main reasons for this are: The electric current passing through a conductor generates a magnetic field that is tying together the current path in the centre of the conductor, and the impedance is the lowest in the centre of the conductor.

Referring to **Fig.19**, a typical flow of small electrical currents in a conductor is illustrated.

In reality, however, the electric current may not flow in a "straight" line from one connection pole to the other (similar to the shape of electric lightening in the sky).

At a certain level of electric current the generated magnetic field is large enough to cause a permanent magnetization of the Ferro-magnetic shaft material. As the electric current is flowing near or at the centre of the SH, the permanently stored magnetic field will reside at the same location: near or at the centre of the SH. When now applying mechanical torque or linear force for oscillation/reciprocation to the shaft, then shaft internally stored magnetic field will respond by tilting its magnetic flux path in accordance to the applied mechanical force. As the permanently stored magnetic field lies deep below the shaft surface the measurable effects are very small, not uniform and therefore not sufficient to build a reliable NCT sensor system.

Referring to **Fig.20**, a uniform current density in a conductor at saturation level is shown.

Only at the saturation level is the electric current density (when applying DC) evenly distributed at the entire cross section of the conductor. The amount of electrical current to achieve this saturation level is extremely high and is mainly influenced by the cross section and conductivity (impedance) of the used conductor.

Referring to **Fig.21**, electric current travelling beneath or at the surface of the conductor (Skin-Effect) is shown.

It is also widely assumed that when passing through alternating current (like a radio frequency signal) through a conductor that the signal is passing through the skin layers of the conductor, called the Skin Effect. The chosen frequency of the alternating current defines the "Location / position" and "depth" of the Skin Effect. At high frequencies the electrical current will travel right at or near the surface of the conductor (A) while at lower frequencies (in the 5 to 10 Hz regions for a 20 mm diameter SH) the electrical alternating current will penetrate more the centre of the shafts cross section (E). Also, the relative current density is higher in the current occupied regions at higher AC frequencies in comparison to the relative current density near the centre of the shaft at very low AC frequencies (as there is more space available for the current to flow through).

Referring to **Fig.22**, the electrical current density of an electrical conductor (cross-section 90 deg to the current flow) when passing through the conductor an alternating current at different frequencies is illustrated.

The desired magnetic field design of the PCME sensor technology are two circular magnetic field structures, stored in two layers on top of each other ("Picky-Back"), and running in opposite direction to each other (Counter-Circular).

Again referring to **Fig.13**, a desired magnetic sensor structure is shown: two endless magnetic loops placed on top of each other, running in opposite directions to each other: Counter-Circular "Picky-Back" Field Design.

To make this magnetic field design highly sensitive to mechanical stresses that will be applied to the SH (shaft), and to generate the largest sensor signal possible, the desired magnetic field structure has to be placed nearest to the shaft surface. Placing the circular magnetic fields to close to the centre of the SH will cause damping of the user available sensor-output-signal slope (most of the sensor signal will travel through the Ferro-magnetic shaft material as it has a much higher permeability in comparison to air), and increases the non-uniformity of the sensor signal (in relation to shaft rotation and to axial movements of the shaft in relation to the secondary sensor.

Referring to **Fig.23**, magnetic field structures stored near the shaft surface and stored near the centre of the shaft are illustrated.

It may be difficult to achieve the desired permanent magnetic encoding of the SH when using AC (alternating current) as the polarity of the created magnetic field is constantly changing and therefore may act more as a Degaussing system.

The PCME technology requires that a strong electrical current ("uni-polar" or DC, to prevent erasing of the desired magnetic field structure) is travelling right below the shaft surface (to ensure that the sensor signal will be uniform and measurable at the outside of the shaft). In addition a Counter-Circular, "picky back" magnetic field structure needs to be formed.

It is possible to place the two Counter-Circular magnetic field structures in the shaft by storing them into the shaft one after each other. First the inner layer will be stored in the SH,

and then the outer layer by using a weaker magnetic force (preventing that the inner layer will be neutralized and deleted by accident. To achieve this, the known "permanent" magnet encoding techniques can be applied as described in patents from FAST technology, or by using a combination of electrical current encoding and the "permanent" magnet encoding.

A much simpler and faster encoding process uses "only" electric current to achieve the desired Counter-Circular "Picky-Back" magnetic field structure. The most challenging part here is to generate the Counter-Circular magnetic field.

A uniform electrical current will produce a uniform magnetic field, running around the electrical conductor in a 90 deg angle, in relation to the current direction (A). When placing two conductors side-by-side (B) then the magnetic field between the two conductors seems to cancel-out the effect of each other (C). Although still present, there is no detectable (or measurable) magnetic field between the closely placed two conductors. When placing a number of electrical conductors side-by-side (D) the "measurable" magnetic field seems to go around the outside the surface of the "flat" shaped conductor.

Referring to **Fig.24**, the magnetic effects when looking at the cross-section of a conductor with a uniform current flowing through them are shown.

The "flat" or rectangle shaped conductor has now been bent into a "U"-shape. When passing an electrical current through the "U"-shaped conductor then the magnetic field following the outer dimensions of the "U"-shape is cancelling out the measurable effects in the inner halve of the "U".

Referring to **Fig.25**, the zone inside the "U"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

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When no mechanical stress is applied to the cross-section of a "U"-shaped conductor it seems that there is no magnetic field present inside of the "U" (F). But when bending or twisting the "U"-shaped conductor the magnetic field will no longer follow its original path (90 deg angle to the current flow). Depending on the applied mechanical forces, the magnetic field begins to change slightly its path. At that time the magnetic-field-vector that is caused by the mechanical stress can be sensed and measured at the surface of the conductor, inside and outside of the "U"-shape. Note: This phenomena is applies only at very specific electrical current levels.

The same applies to the "O"-shaped conductor design. When passing a uniform electrical current through an "O"-shaped conductor (Tube) the measurable magnetic effects inside of the "O" (Tube) have cancelled-out each other (G).

Referring to **Fig.26**, the zone inside the "O"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

However, when mechanical stresses are applied to the "O"-shaped conductor (Tube) it becomes evident that there has been a magnetic field present at the inner side of the "O"-shaped conductor. The inner, counter directional magnetic field (as well as the outer magnetic field) begins to tilt in relation to the applied torque stresses. This tilting field can be clearly sensed and measured.

In the following, an Encoding Pulse Design will be described.

To achieve the desired magnetic field structure (Counter-Circular, Picky-Back, Fields Design) inside the SH, according to an exemplary embodiment of a method of the present invention, unipolar electrical current pulses are passed through the Shaft (or SH). By using "pulses" the desired "Skin-Effect" can be achieved. By using a "unipolar" current direction (not changing

the direction of the electrical current) the generated magnetic effect will not be erased accidentally.

The used current pulse shape is most critical to achieve the desired PCME sensor design. Each parameter has to be accurately and repeatable controlled: Current raising time, Constant current on-time, Maximal current amplitude, and Current falling time. In addition it is very critical that the current enters and exits very uniformly around the entire shaft surface.

In the following, a Rectangle Current Pulse Shape will be described.

Referring to **Fig.27**, a rectangle shaped electrical current pulse is illustrated.

A rectangle shaped current pulse has a fast raising positive edge and a fast falling current edge. When passing a rectangle shaped current pulse through the SH, the raising edge is responsible for forming the targeted magnetic structure of the PCME sensor while the flat "on" time and the falling edge of the rectangle shaped current pulse are counter productive.

Referring to **Fig.28**, a relationship between rectangles shaped Current Encoding Pulse-Width (Constant Current On-Time) and Sensor Output Signal Slope is shown.

In the following example a rectangle shaped current pulse has been used to generate and store the Couter-Circilar "Picky-Back" field in a 15 mm diameter, 14CrNi14 shaft. The pulsed electric current had its maximum at around 270 Ampere. The pulse "on-time" has been electronically controlled. Because of the high frequency component in the rising and falling edge of the encoding pulse, this experiment can not truly represent the effects of a true DC encoding SH. Therefore the Sensor-Output-Signal Slope-curve eventually flattens-out at above 20 mV/Nm when passing the Constant-Current On-Time of 1000 ms.

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Without using a fast raising current-pulse edge (like using a controlled ramping slope) the sensor output signal slope would have been very poor (below 10 mV/Nm). Note: In this experiment (using 14CrNi14) the signal hysteresis was around 0.95% of the FS signal (FS = 75 Nm torque).

Referring to **Fig.29**, increasing the Sensor-Output Signal-Slope by using several rectangle shaped current pulses in succession is shown.

The Sensor-Output-Signal slope can be improved when using several rectangle shaped current-encoding-pulses in successions. In comparisons to other encoding-pulse-shapes the fast falling current-pulse signal slope of the rectangle shaped current pulse will prevent that the Sensor-Output-Signal slope may ever reach an optimal performance level. Meaning that after only a few current pulses (2 to 10) have been applied to the SH (or Shaft) the Sensor-Output Signal-Slope will no longer rise.

In the following, a Discharge Current Pulse Shape is described.

The Discharge-Current-Pulse has no Constant-Current ON-Time and has no fast falling edge. Therefore the primary and most felt effect in the magnetic encoding of the SH is the fast raising edge of this current pulse type.

As shown in **Fig.30**, a sharp raising current edge and a typical discharging curve provides best results when creating a PCME sensor.

Referring to **Fig.31**, a PCME Sensor-Output Signal-Slope optimization by identifying the right pulse current is illustrated.

At the very low end of the pulse current scale (0 to 75 A for a 15 mm diameter shaft, 14CrNi14 shaft material) the "Discharge-Current-Pulse type is not powerful enough to cross the magnetic threshold needed to create a lasting magnetic field inside the Ferro magnetic shaft. When increasing the pulse current amplitude the double circular magnetic field structure begins to form below the shaft surface. As the pulse current amplitude increases so does the achievable torque sensor-output signal-amplitude of the secondary sensor system. At around 400A to 425A the optimal PCME sensor design has been achieved (the two counter flowing magnetic regions have reached their most optimal distance to each other and the correct flux density for best sensor performances.

Referring to **Fig.32**, Sensor Host (SH) cross section with the optimal PCME electrical current density and location during the encoding pulse is illustrated.

When increasing further the pulse current amplitude the absolute, torque force related, sensor signal amplitude will further increase (curve 2) for some time while the overall PCME-typical sensor performances will decrease (curve 1). When passing 900A Pulse Current Amplitude (for a 15 mm diameter shaft) the absolute, torque force related, sensor signal amplitude will begin to drop as well (curve 2) while the PCME sensor performances are now very poor (curve 1).

Referring to **Fig.33**, Sensor Host (SH) cross sections and the electrical pulse current density at different and increasing pulse current levels is shown.

As the electrical current occupies a larger cross section in the SH the spacing between the inner circular region and the outer (near the shaft surface) circular region becomes larger.

Referring to **Fig.34**, better PCME sensor performances will be achieved when the spacing between the Counter-Circular "Picky-Back" Field design is narrow (A).

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The desired double, counter flow, circular magnetic field structure will be less able to create a close loop structure under torque forces which results in a decreasing secondary sensor signal amplitude.

Referring to **Fig.35**, flattening-out the current-discharge curve will also increase the Sensor-Output Signal-Slope.

When increasing the Current-Pulse discharge time (making the current pulse wider) (B) the Sensor-Output Signal-Slope will increase. However the required amount of current is very high to reduce the slope of the falling edge of the current pulse. It might be more practical to use a combination of a high current amplitude (with the optimal value) and the slowest possible discharge time to achieve the highest possible Sensor-Output Signal Slope.

In the following, Electrical Connection Devices in the frame of Primary Sensor Processing will be described.

The PCME technology (it has to be noted that the term 'PCME' technology is used to refer to exemplary embodiments of the present invention) relies on passing through the shaft very high amounts of pulse-modulated electrical current at the location where the Primary Sensor should be produced. When the surface of the shaft is very clean and highly conductive a multi-point Cupper or Gold connection may be sufficient to achieve the desired sensor signal uniformity. Important is that the Impedance is identical of each connection point to the shaft surface. This can be best achieved when assuring the cable length (L) is identical before it joins the main current connection point (I).

Referring to **Fig.36**, a simple electrical multi-point connection to the shaft surface is illustrated.

However, in most cases a reliable and repeatable multi-point electrical connection can be only achieved by ensuring that the impedance at each connection point is identical and constant. Using a spring pushed, sharpened connector will penetrate possible oxidation or isolation layers (maybe caused by finger prints) at the shaft surface.

Referring to **Fig.37**, a multi channel, electrical connecting fixture, with spring loaded contact points is illustrated.

When processing the shaft it is most important that the electrical current is injected and extracted from the shaft in the most uniform way possible. The above drawing shows several electrical, from each other insulated, connectors that are held by a fixture around the shaft. This device is called a Shaft-Processing-Holding-Clamp (or SPHC). The number of electrical connectors required in a SPHC depends on the shafts outer diameter. The larger the outer diameter, the more connectors are required. The spacing between the electrical conductors has to be identical from one connecting point to the next connecting point. This method is called Symmetrical-"Spot"-Contacts.

Referring to **Fig.38**, it is illustrated that increasing the number of electrical connection points will assist the efforts of entering and exiting the Pulse-Modulated electrical current. It will also increase the complexity of the required electronic control system.

Referring to **Fig.39**, an example of how to open the SPHC for easy shaft loading is shown.

In the following, an encoding scheme in the frame of Primary Sensor Processing will be described.

The encoding of the primary shaft can be done by using permanent magnets applied at a rotating shaft or using electric currents passing through the desired section of the shaft. When using permanent magnets a very complex, sequential procedure is necessary to put the two layers of closed loop magnetic fields, on top of each other, in the shaft. When using the PCME procedure the electric current has to enter the shaft and exit the shaft in the most symmetrical way possible to achieve the desired performances.

Referring to **Fig.40**, two SPHCs (Shaft Processing Holding Clamps) are placed at the borders of the planned sensing encoding region. Through one SPHC the pulsed electrical current (I) will enter the shaft, while at the second SPHC the pulsed electrical current (I) will exit the shaft. The region between the two SPHCs will then turn into the primary sensor.

This particular sensor process will produce a Single Field (SF) encoded region. One benefit of this design (in comparison to those that are described below) is that this design is insensitive to any axial shaft movements in relation to the location of the secondary sensor devices. The disadvantage of this design is that when using axial (or in-line) placed MFS coils the system will be sensitive to magnetic stray fields (like the earth magnetic field).

Referring to **Fig.41**, a Dual Field (DF) encoded region (meaning two independent functioning sensor regions with opposite polarity, side-by-side) allows cancelling the effects of uniform magnetic stray fields when using axial (or in-line) placed MFS coils. However, this primary sensor design also shortens the tolerable range of shaft movement in axial direction (in relation to the location of the MFS coils). There are two ways to produce a Dual Field (DF) encoded region with the PCME technology. The sequential process, where the magnetic encoded sections are produced one after each other, and the parallel process, where both magnetic encoded sections are produced at the same time.

The first process step of the sequential dual field design is to magnetically encode one sensor section (identically to the Single Field procedure), whereby the spacing between the two SPHC has to be halve of the desired final length of the Primary Sensor region. To simplify the explanations of this process we call the SPHC that is placed in the centre of the final Primary Sensor Region the Centre SPHC (C-SPHC), and the SPHC that is located at the left side of the Centre SPHC: L-SPHC.

Referring to **Fig.42**, the second process step of the sequential Dual Field encoding will use the SPHC that is located in the centre of the Primary Sensor region (called C-SPHC) and a second SPHC that is placed at the other side (the right side) of the centre SPHC, called R-SPHC. Important is that the current flow direction in the centre SPHC (C-SPHC) is identical at both process steps.

Referring to **Fig.43**, the performance of the final Primary Sensor Region depends on how close the two encoded regions can be placed in relation to each other. And this is dependent on the design of the used centre SPHC. The narrower the in-line space contact dimensions are of the C-SPHC, the better are the performances of the Dual Field PCME sensor.

Fig.44 shows the pulse application according to another exemplary embodiment of the present invention. As my be taken from the above drawing, the pulse is applied to three locations of the shaft. Due to the current distribution to both sides of the middle electrode where the current I is entered into the shaft, the current leaving the shaft at the lateral electrodes is only half the current entered at the middle electrode, namely ½ I. The electrodes are depicted as rings which dimensions are adapted to the dimensions of the outer surface of the shaft. However, it has to be noted that other electrodes may be used, such as the electrodes comprising a plurality of pin electrodes described later in this text.

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Referring to **Fig.45,** magnetic flux directions of the two sensor sections of a Dual Field PCME sensor design are shown when no torque or linear motion stress is applied to the shaft. The counter flow magnetic flux loops do not interact with each other.

Referring to **Fig.46,** when torque forces or linear stress forces are applied in a particular direction then the magnetic flux loops begin to run with an increasing tilting angle inside the shaft. When the tilted magnetic flux reaches the PCME segment boundary then the flux line interacts with the counterflowing magnetic flux lines, as shown.

Referring to **Fig.47,** when the applied torque direction is changing (for example from clock-wise to counter-clock-wise) so will change the tilting angle of the counterflow magnetic flux structures inside the PCM Encoded shaft.

In the following, a Multi Channel Current Driver for Shaft Processing will be described.

In cases where an absolute identical impedance of the current path to the shaft surface can not be guaranteed, then electric current controlled driver stages can be used to overcome this problem.

Referring to **Fig.48,** a six-channel synchronized Pulse current driver system for small diameter Sensor Hosts (SH) is shown. As the shaft diameter increases so will the number of current driver channels.

In the following, Bras Ring Contacts and Symmetrical "Spot" Contacts will be described.

When the shaft diameter is relative small and the shaft surface is clean and free from any oxidations at the desired Sensing Region, then a simple "Bras"-ring (or Copper-ring) contact method can be chosen to process the Primary Sensor.

Referring to **Fig.49**, bras-rings (or Copper-rings) tightly fitted to the shaft surface may be used, with solder connections for the electrical wires. The area between the two Bras-rings (Copper-rings) is the encoded region.

However, it is very likely that the achievable RSU performances are much lower then when using the Symmetrical "Spot" Contact method.

In the following, a Hot-Spotting concept will be described.

A standard single field (SF) PCME sensor has very poor Hot-Spotting performances. The external magnetic flux profile of the SF PCME sensor segment (when torque is applied) is very sensitive to possible changes (in relation to Ferro magnetic material) in the nearby environment. As the magnetic boundaries of the SF encoded sensor segment are not well defined (not "Pinned Down") they can "extend" towards the direction where Ferro magnet material is placed near the PCME sensing region.

Referring to **Fig.50**, a PCME process magnetized sensing region is very sensitive to Ferro magnetic materials that may come close to the boundaries of the sensing regions.

To reduce the Hot-Spotting sensor sensitivity the PCME sensor segment boundaries have to be better defined by pinning them down (they can no longer move).

Referring to **Fig.51**, a PCME processed Sensing region with two "Pinning Field Regions" is shown, one on each side of the Sensing Region.

By placing Pinning Regions closely on either side the Sensing Region, the Sensing Region Boundary has been pinned down to a very specific location. When Ferro magnetic material is

coming close to the Sensing Region, it may have an effect on the outer boundaries of the Pinning Regions, but it will have very limited effects on the Sensing Region Boundaries.

There are a number of different ways, according to exemplary embodiments of the present invention how the SH (Sensor Host) can be processed to get a Single Field (SF) Sensing Region and two Pinning Regions, one on each side of the Sensing Region. Either each region is processed after each other (Sequential Processing) or two or three regions are processed simultaneously (Parallel Processing). The Parallel Processing provides a more uniform sensor (reduced parasitic fields) but requires much higher levels of electrical current to get to the targeted sensor signal slope.

Referring to **Fig.52**, a parallel processing example for a Single Field (SF) PCME sensor with Pinning Regions on either side of the main sensing region is illustrated, in order to reduce (or even eliminate) Hot-Spotting.

A Dual Field PCME Sensor is less sensitive to the effects of Hot-Spotting as the sensor centre region is already Pinned-Down. However, the remaining Hot-Spotting sensitivity can be further reduced by placing Pinning Regions on either side of the Dual-Field Sensor Region.

Referring to **Fig.53**, a Dual Field (DF) PCME sensor with Pinning Regions either side is shown.

When Pinning Regions are not allowed or possible (example: limited axial spacing available) then the Sensing Region has to be magnetically shielded from the influences of external Ferro Magnetic Materials.

In the following, the Rotational Signal Uniformity (RSU) will be explained.

The RSU sensor performance are, according to current understanding, mainly depending on how circumferentially uniform the electrical current entered and exited the SH surface, and the physical space between the electrical current entry and exit points. The larger the spacing between the current entry and exit points, the better is the RSU performance.

Referring to **Fig.54**, when the spacings between the individual circumferential placed current entry points are relatively large in relation to the shaft diameter (and equally large are the spacings between the circumferentially placed current exit points) then this will result in very poor RSU performances. In such a case the length of the PCM Encoding Segment has to be as large as possible as otherwise the created magnetic field will be circumferentially non-uniform.

Referring to **Fig.55**, by widening the PCM Encoding Segment the circumferentially magnetic field distribution will become more uniform (and eventually almost perfect) at the halve distance between the current entry and current exit points. Therefore the RSU performance of the PCME sensor is best at the halve way-point between of the current-entry / current-exit points.

Next, the basic design issues of a NCT sensor system will be described.

Without going into the specific details of the PCM-Encoding technology, the end-user of this sensing technology need to now some design details that will allow him to apply and to use this sensing concept in his application. The following pages describe the basic elements of a magnetostriction based NCT sensor (like the primary sensor, secondary sensor, and the SCSP

electronics), what the individual components look like, and what choices need to be made when integrating this technology into an already existing product.

In principle the PCME sensing technology can be used to produce a stand-alone sensor product. However, in already existing industrial applications there is little to none space available for a "stand-alone" product. The PCME technology can be applied in an existing product without the need of redesigning the final product.

In case a stand-alone torque sensor device or position detecting sensor device will be applied to a motor-transmission system it may require that the entire system need to undergo a major design change.

In the following, referring to Fig.56, a possible location of a PCME sensor at the shaft of an engine is illustrated.

Next, Sensor Components will be explained.

A non-contact magnetostriction sensor (NCT-Sensor), as shown in **Fig.57**, may consist, according to an exemplary embodiment of the present invention, of three main functional elements: The Primary Sensor, the Secondary Sensor, and the Signal Conditioning & Signal Processing (SCSP) electronics.

Depending on the application type (volume and quality demands, targeted manufacturing cost, manufacturing process flow) the customer can chose to purchase either the individual components to build the sensor system under his own management, or can subcontract the production of the individual modules.

Fig.58 shows a schematic illustration of components of a non-contact torque sensing device. However, these components can also be implemented in a non-contact position sensing device.

In cases where the annual production target is in the thousands of units it may be more efficient to integrate the "primary-sensor magnetic-encoding-process" into the customers manufacturing process. In such a case the customer needs to purchase application specific "magnetic encoding equipment".

In high volume applications, where cost and the integrity of the manufacturing process are critical, it is typical that NCTE supplies only the individual basic components and equipment necessary to build a non-contact sensor:

- ☐ ICs (surface mount packaged, Application-Specific Electronic Circuits)
- ☐ MFS-Coils (as part of the Secondary Sensor)
- ☐ Sensor Host Encoding Equipment (to apply the magnetic encoding on the shaft = Primary Sensor)

Depending on the required volume, the MFS-Coils can be supplied already assembled on a frame, and if desired, electrically attached to a wire harness with connector. Equally the SCSP (Signal Conditioning & Signal Processing) electronics can be supplied fully functional in PCB format, with or without the MFS-Coils embedded in the PCB.

Fig.59 shows components of a sensing device.

As can be seen from **Fig.60**, the number of required MFS-coils is dependent on the expected sensor performance and the mechanical tolerances of the physical sensor design. In a well designed sensor system with perfect Sensor Host (SH or magnetically encoded shaft) and

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minimal interferences from unwanted magnetic stray fields, only 2 MFS-coils are needed. However, if the SH is moving radial or axial in relation to the secondary sensor position by more than a few tenths of a millimeter, then the number of MFS-coils need to be increased to achieve the desired sensor performance.

In the following, a control and/or evaluation circuitry will be explained.

The SCSP electronics, according to an exemplary embodiment of the present invention, consist of the NCTE specific ICs, a number of external passive and active electronic circuits, the printed circuit board (PCB), and the SCSP housing or casing. Depending on the environment where the SCSP unit will be used the casing has to be sealed appropriately.

Depending on the application specific requirements NCTE (according to an exemplary embodiment of the present invention) offers a number of different application specific circuits:

- ☐ Basic Circuit
- ☐ Basic Circuit with integrated Voltage Regulator
- ☐ High Signal Bandwidth Circuit
- ☐ Optional High Voltage and Short Circuit Protection Device
- ☐ Optional Fault Detection Circuit

Fig.61 shows a single channel, low cost sensor electronics solution.

Fig.62 shows a dual channel, short circuit protected system design with integrated fault detection. This design consists of 5 ASIC devices and provides a high degree of system safety. The Fault-Detection IC identifies when there is a wire breakage anywhere in the

sensor system, a fault with the MFS coils, or a fault in the electronic driver stages of the "Basic IC".

Next, the Secondary Sensor Unit will be explained.

The Secondary Sensor may, according to one embodiment shown in **Fig.63**, consist of the elements: One to eight MFS (Magnetic Field Sensor) Coils, the Alignment- & Connection-Plate, the wire harness with connector, and the Secondary-Sensor-Housing.

The MFS-coils may be mounted onto the Alignment-Plate. Usually the Alignment-Plate allows that the two connection wires of each MFS-Coil are soldered / connected in the appropriate way. The wire harness is connected to the alignment plate. This, completely assembled with the MFS-Coils and wire harness, is then embedded or held by the Secondary-Sensor-Housing.

The main element of the MFS-Coil is the core wire, which has to be made out of an amorphous-like material.

Depending on the environment where the Secondary-Sensor-Unit will be used, the assembled Alignment Plate has to be covered by protective material. This material can not cause mechanical stress or pressure on the MFS-coils when the ambient temperature is changing.

In applications where the operating temperature will not exceed +110 deg C the customer has the option to place the SCSP electronics (ASIC) inside the secondary sensor unit (SSU). While the ASIC devices can operated at temperatures above +125 deg C it will become increasingly more difficult to compensate the temperature related signal-offset and signal-gain changes.

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The recommended maximal cable length between the MFS-coils and the SCSP electronics is 2 meters. When using the appropriate connecting cable, distances of up to 10 meters are achievable. To avoid signal-cross-talk in multi-channel applications (two independent SSUs operating at the same Primary Sensor location = Redundant Sensor Function), specially shielded cable between the SSUs and the SCSP Electronics should be considered.

When planning to produce the Secondary-Sensor-Unit (SSU) the producer has to decide which part / parts of the SSU have to be purchased through subcontracting and which manufacturing steps will be made in-house.

In the following, Secondary Sensor Unit Manufacturing Options will be described.

When integrating the NCT-Sensor into a customized tool or standard transmission system then the systems manufacturer has several options to choose from:

- ☐ custom made SSU (including the wire harness and connector)
- ☐ selected modules or components; the final SSU assembly and system test may be done under the customer's management.
- ☐ only the essential components (MFS-coils or MFS-core-wire, Application specific ICs) and will produce the SSU in-house.

Fig.64 illustrates an exemplary embodiment of a Secondary Sensor Unit Assembly.

Next, a Primary Sensor Design is explained.

The SSU (Secondary Sensor Units) can be placed outside the magnetically encoded SH (Sensor Host) or, in case the SH is hollow, inside the SH. The achievable sensor signal

amplitude is of equal strength but has a much better signal-to-noise performance when placed inside the hollow shaft.

Fig.65 illustrates two configurations of the geometrical arrangement of Primary Sensor and Secondary Sensor.

Improved sensor performances may be achieved when the magnetic encoding process is applied to a straight and parallel section of the SH (shaft). For a shaft with 15 mm to 25 mm diameter the optimal minimum length of the Magnetically Encoded Region is 25 mm. The sensor performances will further improve if the region can be made as long as 45 mm (adding Guard Regions). In complex and highly integrated transmission (gearbox) systems it will be difficult to find such space. Under more ideal circumstances, the Magnetically Encoding Region can be as short as 14 mm, but this bears the risk that not all of the desired sensor performances can be achieved.

As illustrated in **Fig.66**, the spacing between the SSU (Secondary Sensor Unit) and the Sensor Host surface, according to an exemplary embodiment of the present invention, should be held as small as possible to achieve the best possible signal quality.

Next, the Primary Sensor Encoding Equipment will be described.

An example is shown in **Fig.67**.

Depending on which magnetostriction sensing technology will be chosen, the Sensor Host (SH) needs to be processed and treated accordingly. The technologies vary by a great deal from each other (ABB, FAST, FT, Kubota, MDI, NCTE, RM, Siemens, ...) and so does the processing equipment required. Some of the available magnetostriction sensing technologies

do not need any physical changes to be made on the SH and rely only on magnetic processing (MDI, FAST, NCTE).

While the MDI technology is a two phase process, the FAST technology is a three phase process, and the NCTE technology a one phase process, called PCM Encoding.

One should be aware that after the magnetic processing, the Sensor Host (SH or Shaft), has become a "precision measurement" device and has to be treated accordingly. The magnetic processing should be the very last step before the treated SH is carefully placed in its final location.

The magnetic processing should be an integral part of the customer's production process (in-house magnetic processing) under the following circumstances:

- ☐ High production quantities (like in the thousands)
- ☐ Heavy or difficult to handle SH (e.g. high shipping costs)
- ☐ Very specific quality and inspection demands (e.g. defense applications)

In all other cases it may be more cost effective to get the SH magnetically treated by a qualified and authorized subcontractor, such as NCTE. For the "in-house" magnetic processing dedicated manufacturing equipment is required. Such equipment can be operated fully manually, semi-automated, and fully automated. Depending on the complexity and automation level the equipment can cost anywhere from EUR 20k to above EUR 500k.

In the following, further embodiments of the invention will be described which may or may not be realized with PCME technology.

Fig.68 and **Fig.69** show schematic views illustrating a sequence of signals 6810 captured by three magnetic field detectors 6800, 6801, 6802 generated by six magnetic encoded regions (see "1" to "6") provided with (from left to right) increasing distances from one another on a reciprocating shaft (not shown) of a position sensor array according to an eighth embodiment of the invention. A first pickup location 6820 and a second pickup location 6830 are shown. The six magnetic encoded regions (markers) have the same physical dimension (width of the markers is constant), but the location in relation to each other is changing.

As can be seen from Fig.69, when using three pickup modules 6800, 6801, 6802, then the usable axial-measurement range is much larger than in a scenario of using one or two pickup modules, since there are no "dead" areas (at least two pickup devices have a usable signal at any given location, at any point of time).

Fig.70 and **Fig.71** show schematic views illustrating a sequence of signals 7000 captured by two magnetic field detectors 6800, 6801 generated by six magnetic encoded regions (see "1" to "6") provided with (from left to right) increasing distances from one another provided on a reciprocating shaft (not shown) of a position sensor array according to a ninth embodiment of the invention.

When using two pickup devices 6800, 6801, the axial measurement range expands considerably than when using only one pickup device. However, there are still "dead" areas 7100 between the markers where there is no sufficient information available through the pickup system. Apart from the "dead" areas 7100, the axial position can be determined accurately. Two pickups enable to determine accurately the axial position when two signals are present at any given location.

Fig.72 shows a schematic view illustrating a sequence of signals 6810 captured by one magnetic field detector 6800 generated by six magnetic encoded regions (see "1" to "6")

provided with (from left to right) increasing distances from one another provided on a reciprocating shaft (not shown) of a position sensor array according to a tenth embodiment of the invention. This embodiment allows to obtain axial position information with low effort.

Fig.73 to Fig.75 show a hollow tube 7300 as reciprocating object with different embodiments for magnetic encoded regions arranged inside the hollow tube. The magnetic field generated inside the tube 7300 has to be strong enough to penetrate the outer tube wall.

According to the embodiment shown in **Fig.73**, a permanent magnet 7301 (synthetic magnet) is placed inside the tube.

According to the embodiment shown in **Fig.74**, a coil 7400 (inductor) is placed inside the tube which can be magnetized by an electrical power source 7401.

According to the embodiment shown in **Fig.75**, a helical coil 7500 is placed inside the tube which can be magnetized by an electrical power source 7401.

Fig.76, **Fig.77** show a position sensor array 7600 according to an eleventh embodiment of the invention.

In an automatic automotive gearbox system, as shown in Fig.76, Fig.77, the position of the various tooth-wheels (gear-wheels) are changed by push-pull-rods 7601. In a passenger car gearbox system may be particularly four or more push-pull-rods 7601 to control the gear positions of the cars transmission system. The push-pull-rods 7601 may be operated by an electric or pneumatic or hydraulic actuator. The actuators operate a hook 7602 which is inserted into a hole from the push-pull-rod 7601.

The push-pull-rod may 7601 move as little as +/-10 mm (passenger car gearbox) or much more (truck gearbox). The optimal operation of the gearbox requires that the push-pull-rods 7601 are moved to precise positions with little tolerances.

As the axial measurement range is relatively short (+/-10mm, up to +/-20mm) only one magnetic marker 103 is required for measuring the position of the push-pull-rod 7601. The magnetic marker 103 can be placed at any desired location of the push-pull-rod 7601 whereby the cross-section of the push-pull-rod 7601 where the marker 103 will be placed can be round, square, rectangle, or any other desired shape. As the push-pull-rod 7601 does not rotate, a non-uniform (non-round) shape of the rod's cross section is acceptable.

Fig.76 shows a typical gearbox push-pull-rod 7601 design, required to change the gear (tooth-wheel) position inside the gearbox by means of an externally placed actuator. The actuator is attached to the hook 7602 which is attached to the end of the push-pull-rod 7601.

Fig.77 shows a detailed view of the push-pull-rod 7601 with an magnetic marker encoding 103 and at least one magnetic field detecting device 104. The magnetic field detecting device 104 (example: coil) will detect the exact axial (linear) position of the push-pull-rod 7601 in relation to the position of the magnetic field detecting device 104.

It should be noted that the term "comprising" does not exclude other elements or steps and the "a" or "an" does not exclude a plurality. Also elements described in association with different embodiments may be combined.

What Is claimed is:

A position sensor device for determining a position of a reciprocating object, comprising

at least one magnetically encoded region fixed on a reciprocating object;

at least one magnetic field detector;

a position determining unit;

wherein the magnetic field detector is adapted to detect a signal generated by the magnetically encoded region when the magnetically encoded region reciprocating with the reciprocating object passes a surrounding area of the magnetic field detector;

wherein the position determining unit is adapted to determine the position of a reciprocating object based on the detected signal;

wherein the at least one magnetically encoded region is formed by a first magnetic flow region oriented in a first direction and by a second magnetic flow region oriented in a second direction, wherein the first direction is opposite to the second direction;

wherein in a cross-sectional view of the reciprocating object, there is the first circular magnetic flow having the first direction and a first radius and the second circular magnetic flow having the second direction and a second radius, wherein the first radius is larger than the second radius.

Abstract

A position sensor device, a position sensor array, a concrete processing apparatus and a method for determining a position of a reciprocating object

A position sensor device for determining a position of a reciprocating object, comprising at least one magnetically encoded region fixed on a reciprocating object, comprising at least one magnetic field detector, and comprising a position determining unit. The magnetic field detector is adapted to detect a signal generated by the magnetically encoded region when the magnetically encoded region reciprocating with the reciprocating object passes a surrounding area of the magnetically encoded region. The position determining unit is adapted to determine a position of a reciprocating object based on the detected magnetic signal.

(Fig.10)

AD:pl

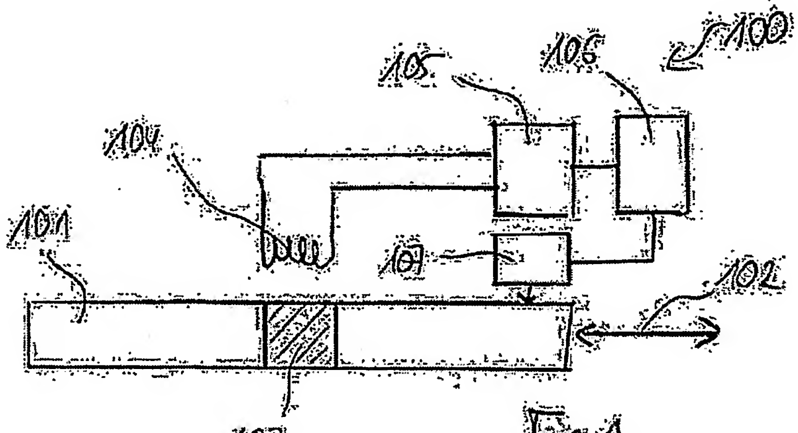


Fig 1

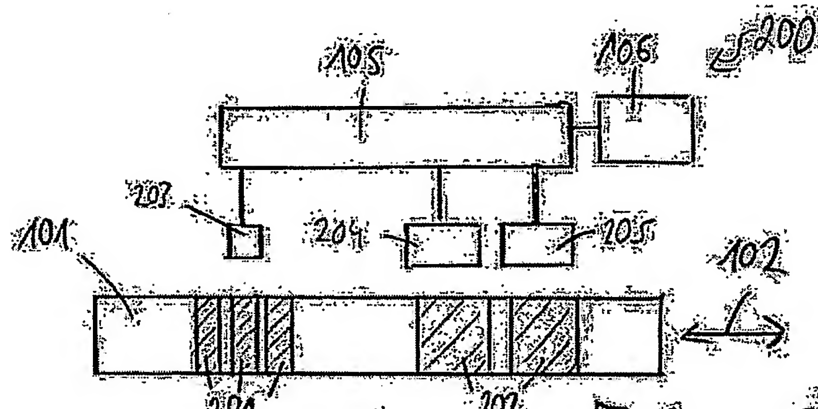


Fig 2

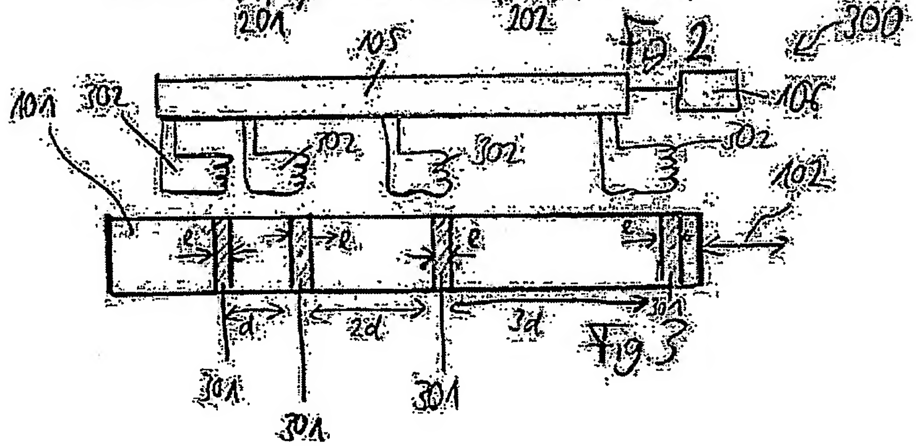


Fig 3

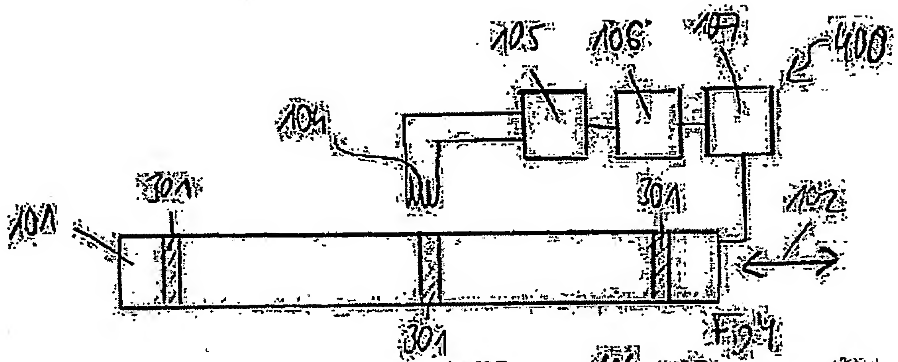


Fig 4

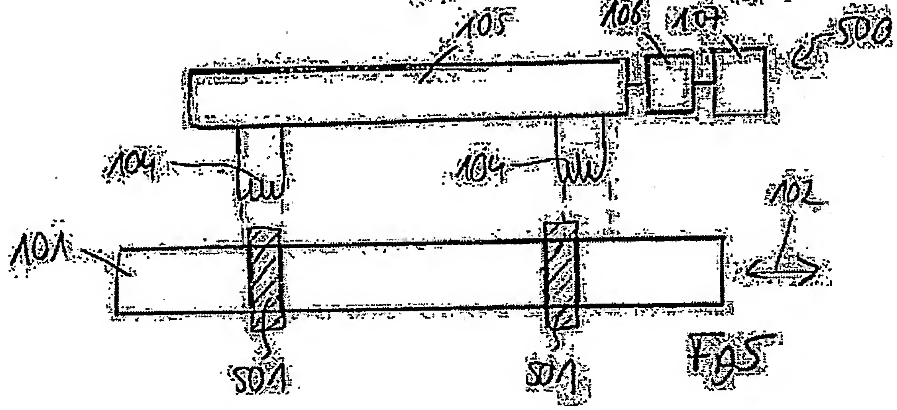


Fig 5

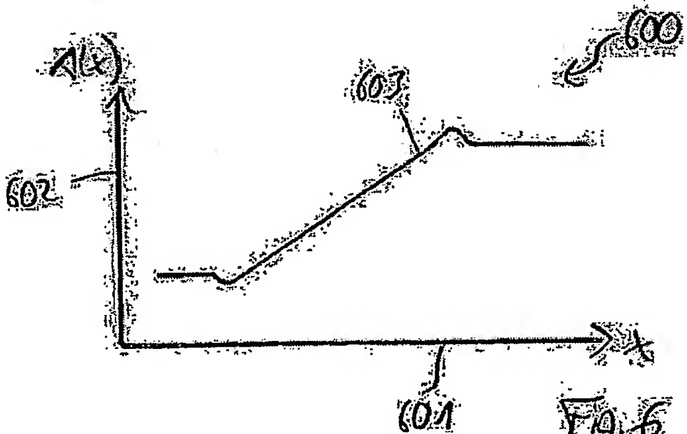


Fig 6

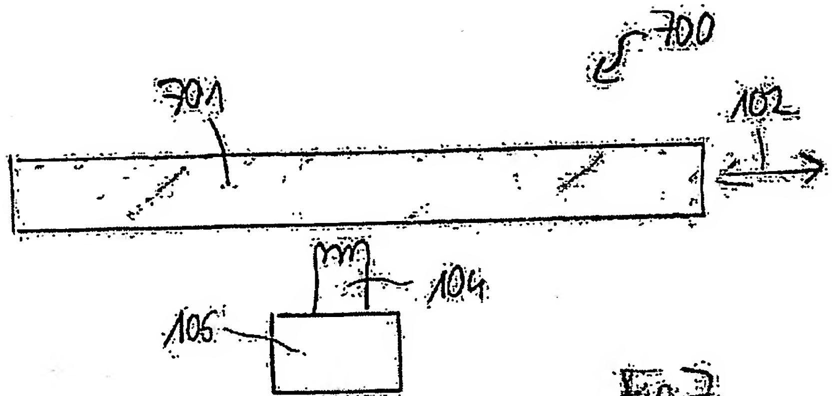


Fig 7

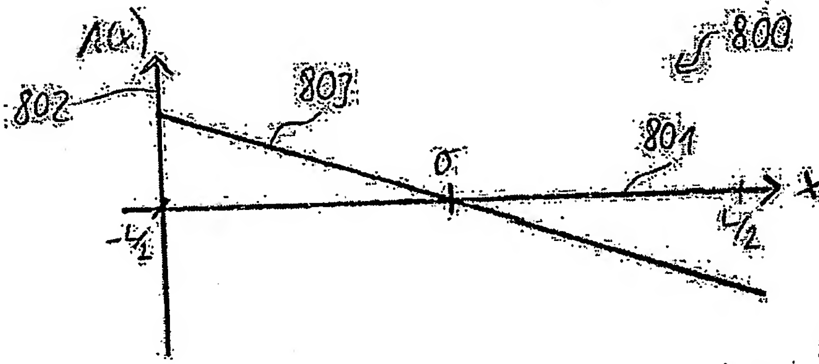


Fig. 8

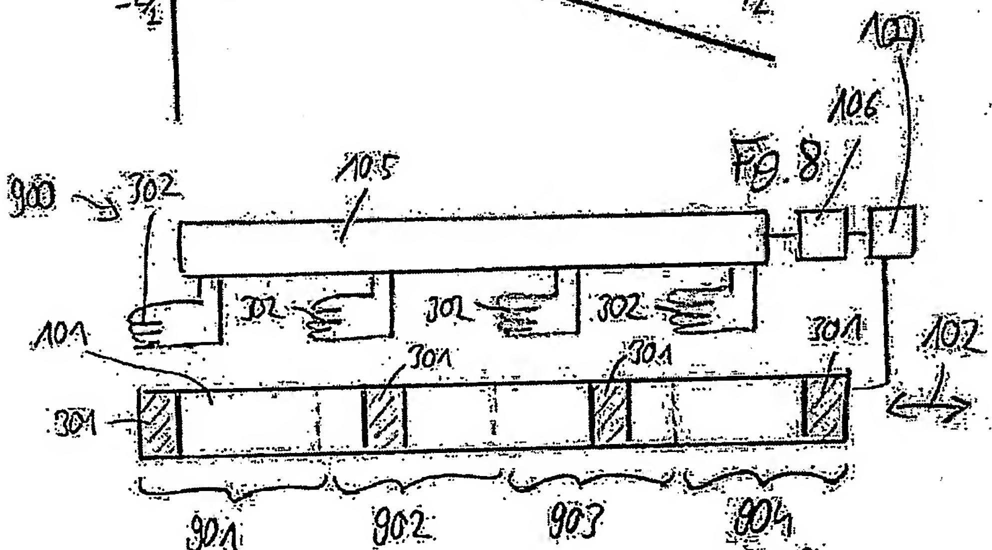
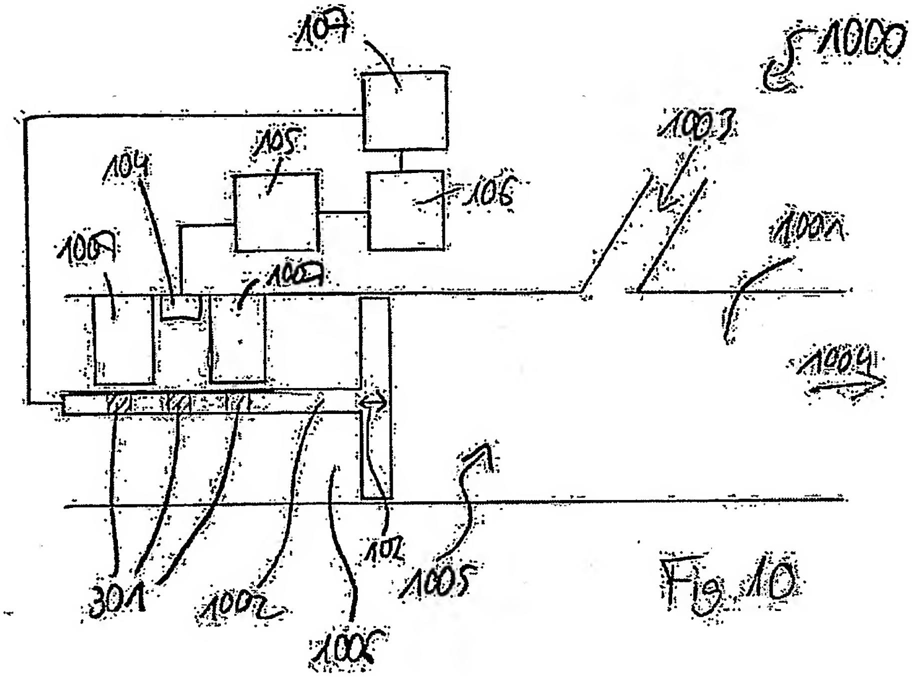
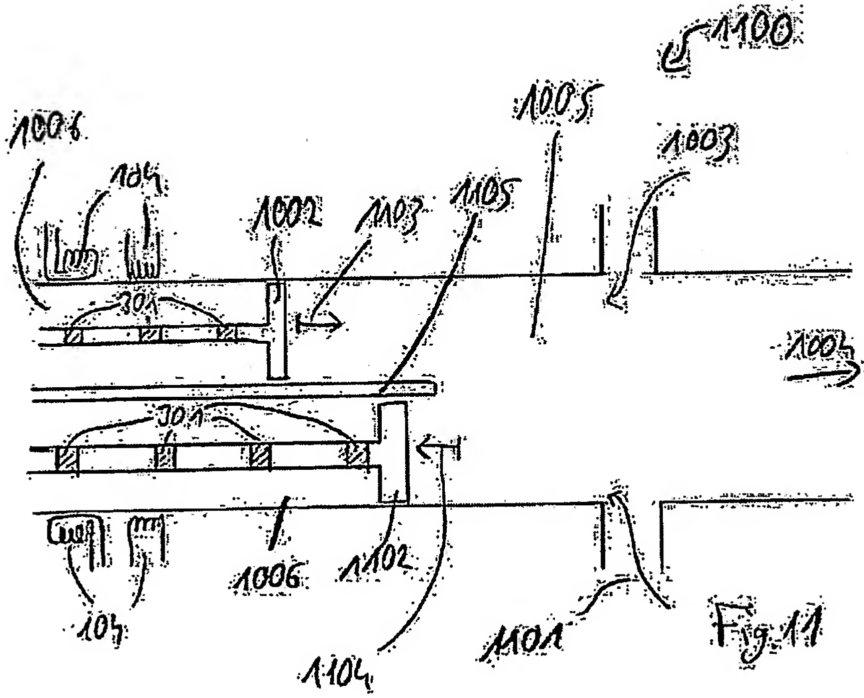


Fig. 9



1000
107
1003
105
104
106
1007
1001
1007
1004
102
301
1002
1005
1006

Fig. 10



1100
1005
1006
1003
104
1002
1103
1105
301
1004
301
1006
1102
103
1101
1104

Fig. 11

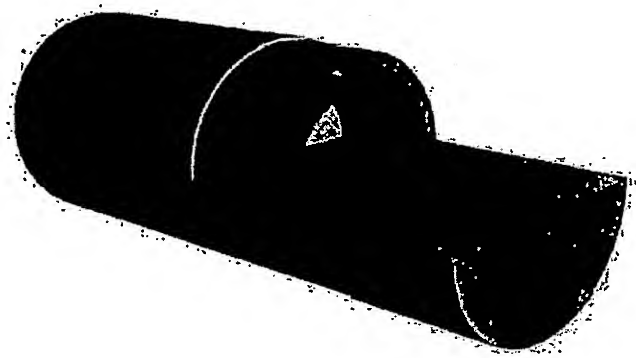


Fig 12

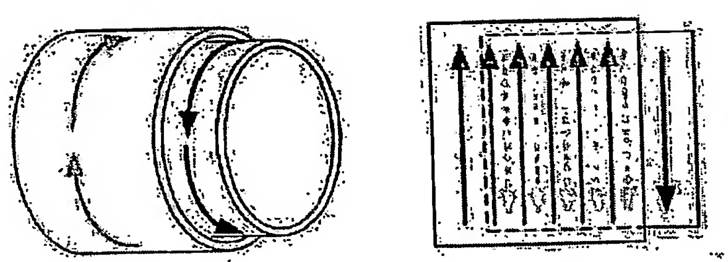


Fig 13

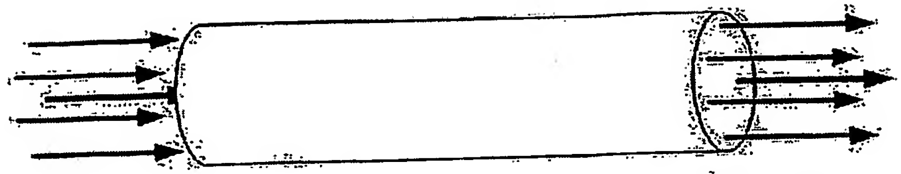


Fig. 17

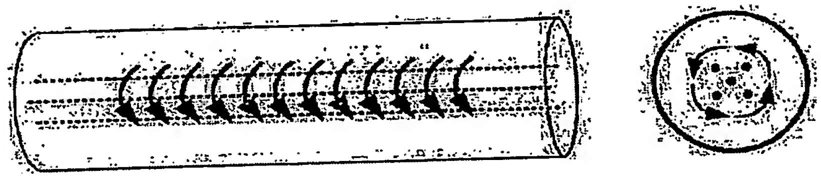


Fig. 18

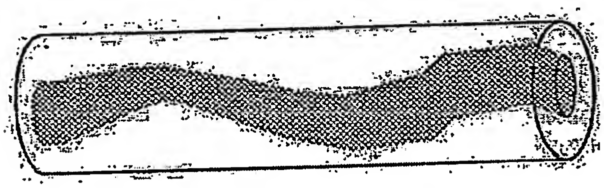


Fig. 19

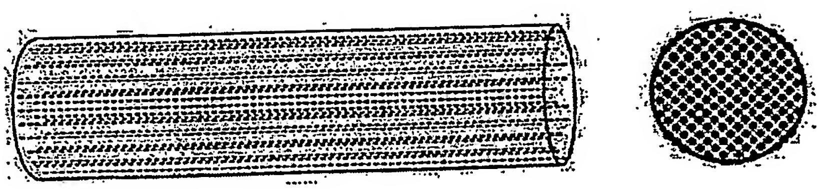


Fig. 20

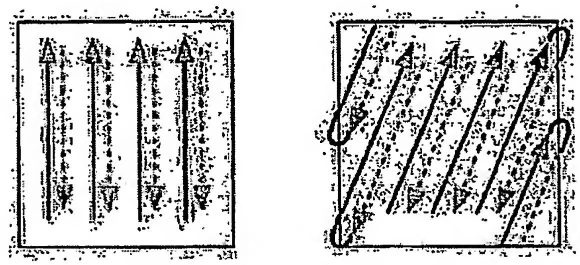


Fig 14

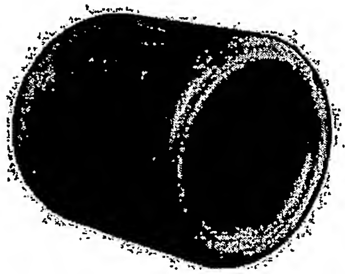


Fig 15

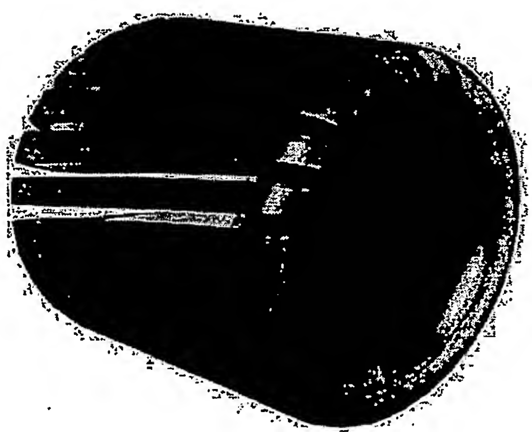


Fig 16

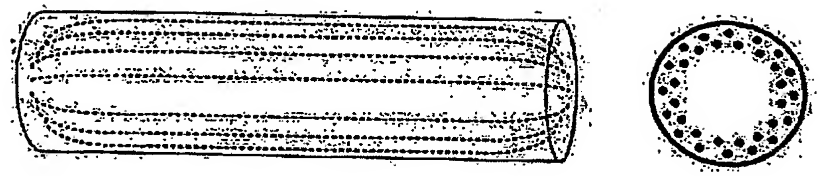


Fig 21

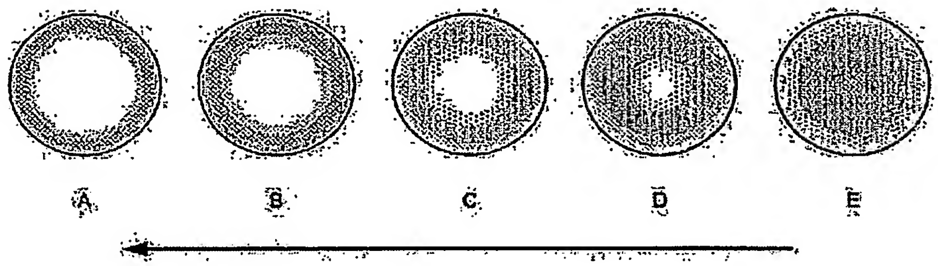


Fig 22

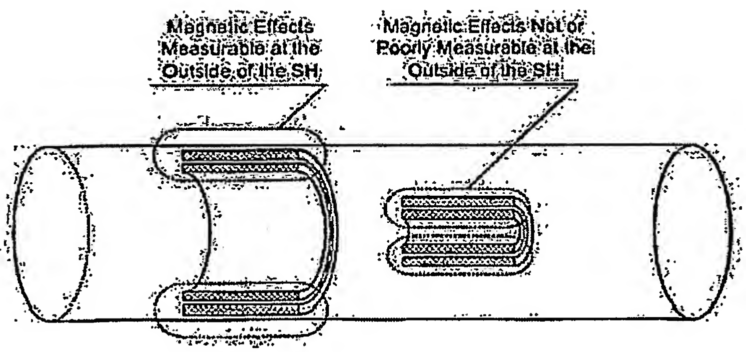


Fig 23

Fig 24

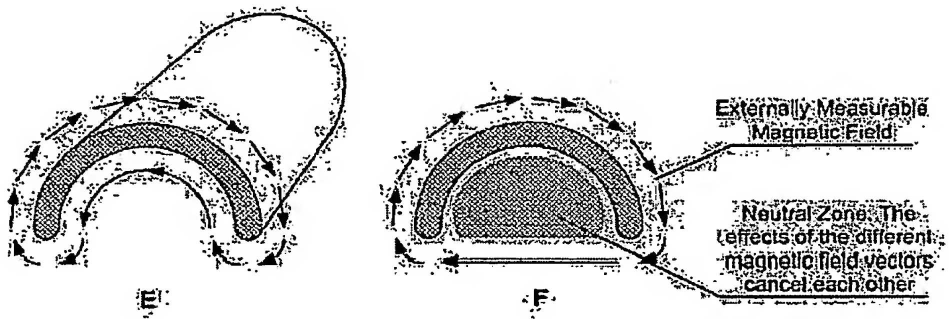


Fig 25

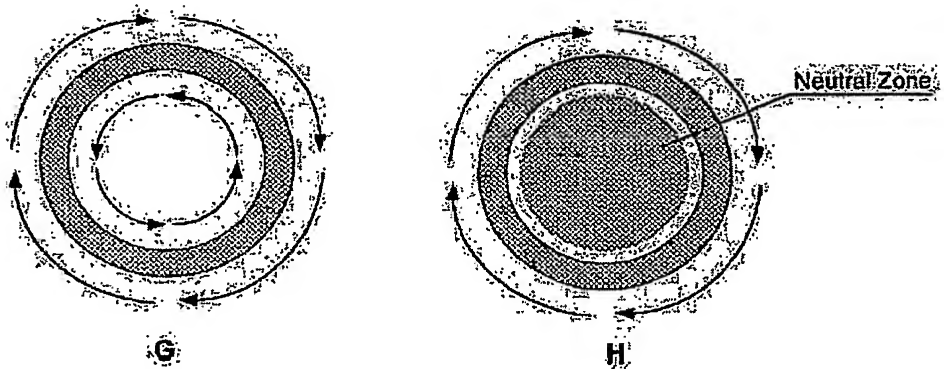
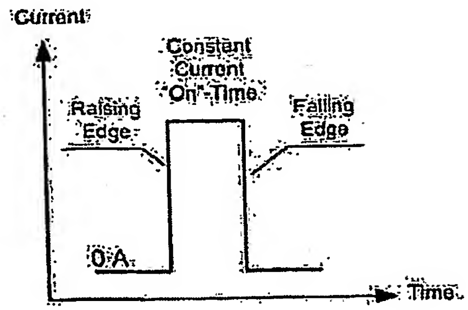
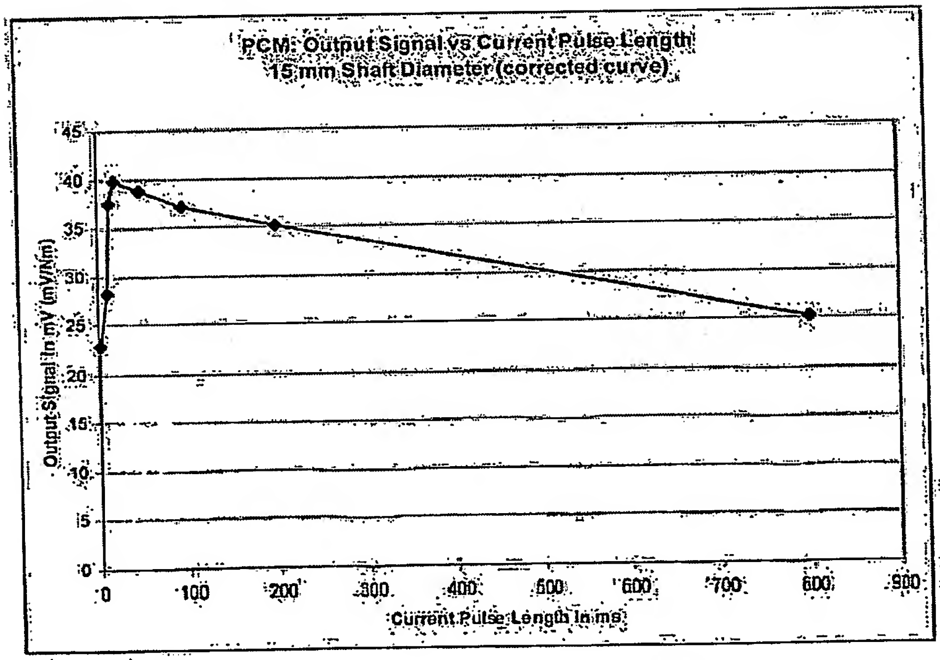


Fig 26



Current
Constant
Current
"On"-Time
Raising
Edge
Falling
Edge
0 A
Time

Fig. 27



PCM: Output Signal vs Current Pulse Length
15 mm Shaft Diameter (corrected curve)
Output Signal in mV (mV/Nm)
0
5
10
15
20
25
30
35
40
45
0
100
200
300
400
500
600
700
800
900
Current Pulse Length in ms

Fig. 28

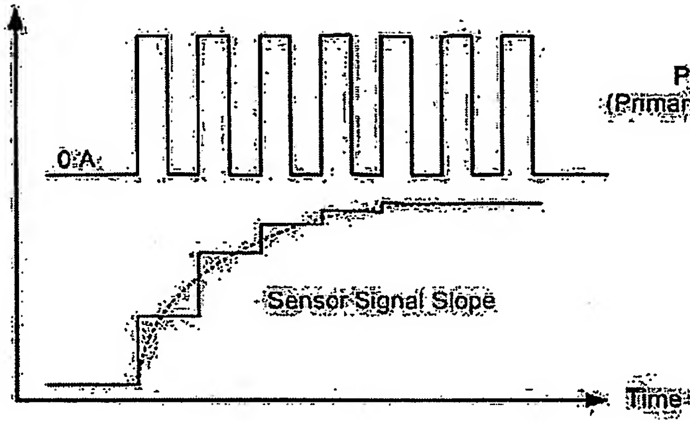


Fig 29

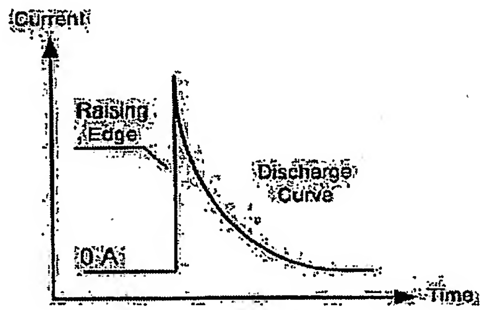


Fig 30

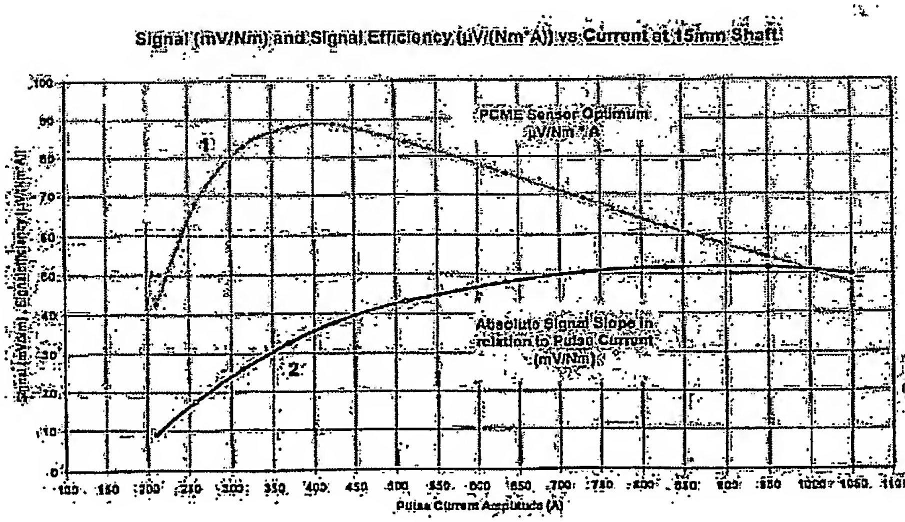


Fig 31

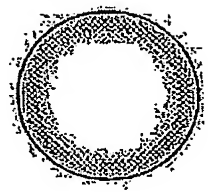


Fig 32

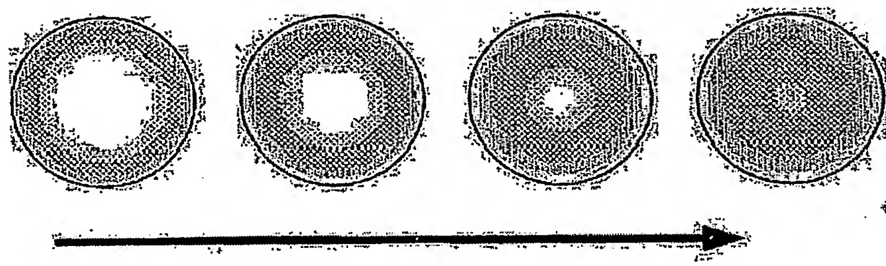


Fig 33

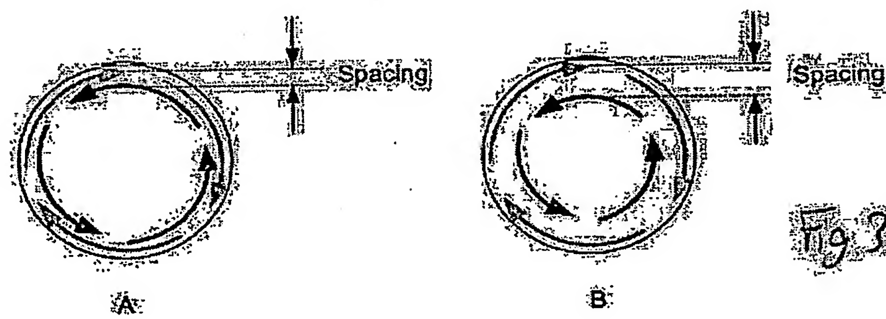


Fig 34

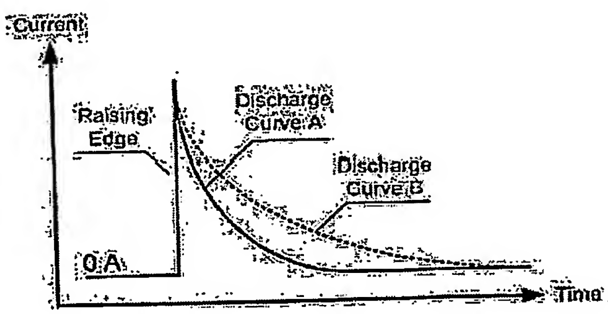


Fig 35

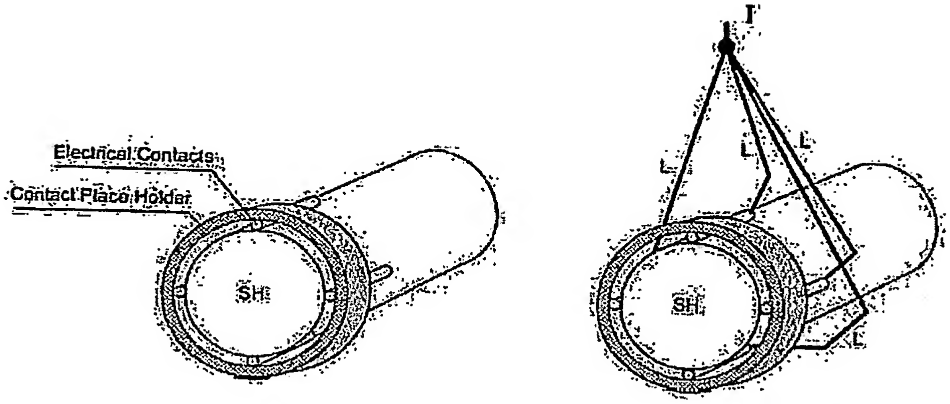


Fig 36

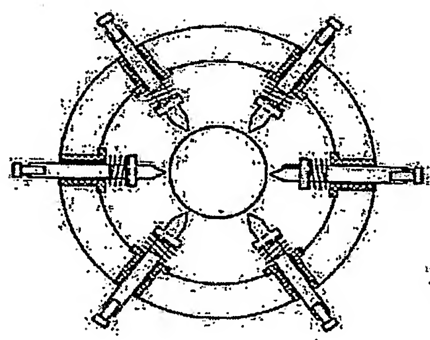


Fig 37

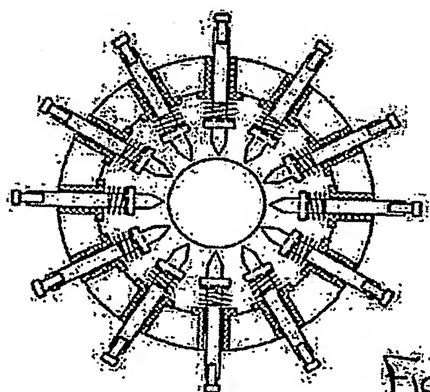


Fig 38

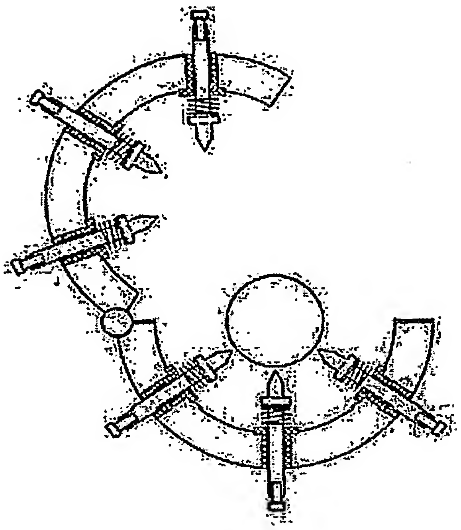


Fig 39

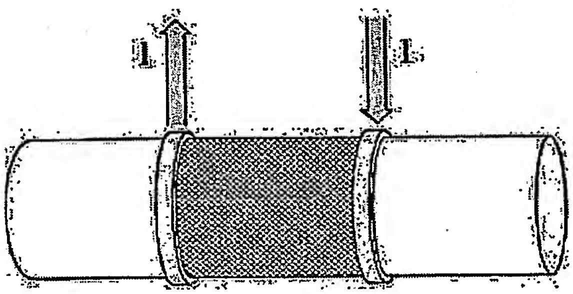


Fig 40

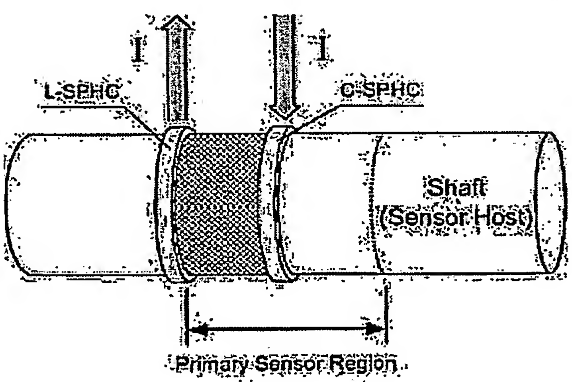


Fig 41

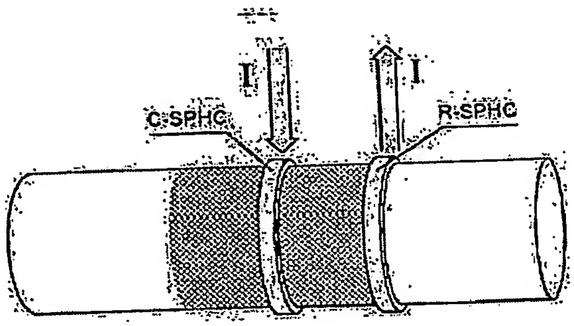


Fig 42

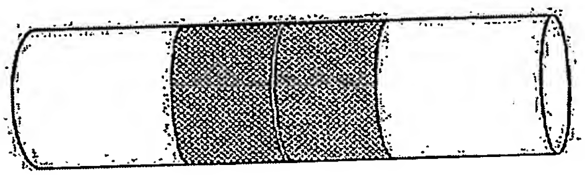


Fig 43

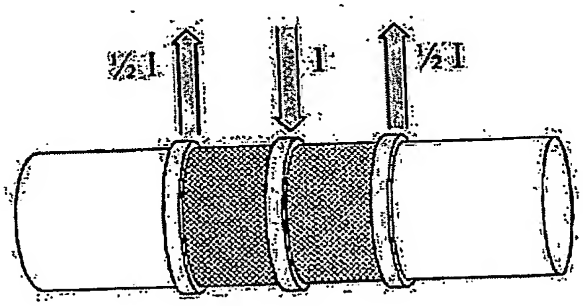


Fig 44

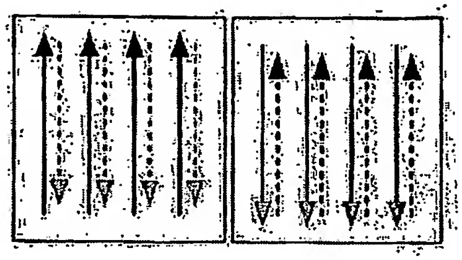


Fig 45

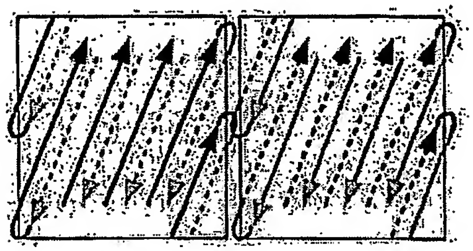


Fig 46

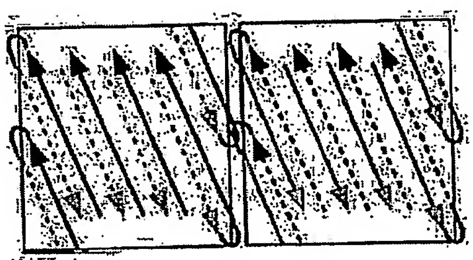


Fig 47

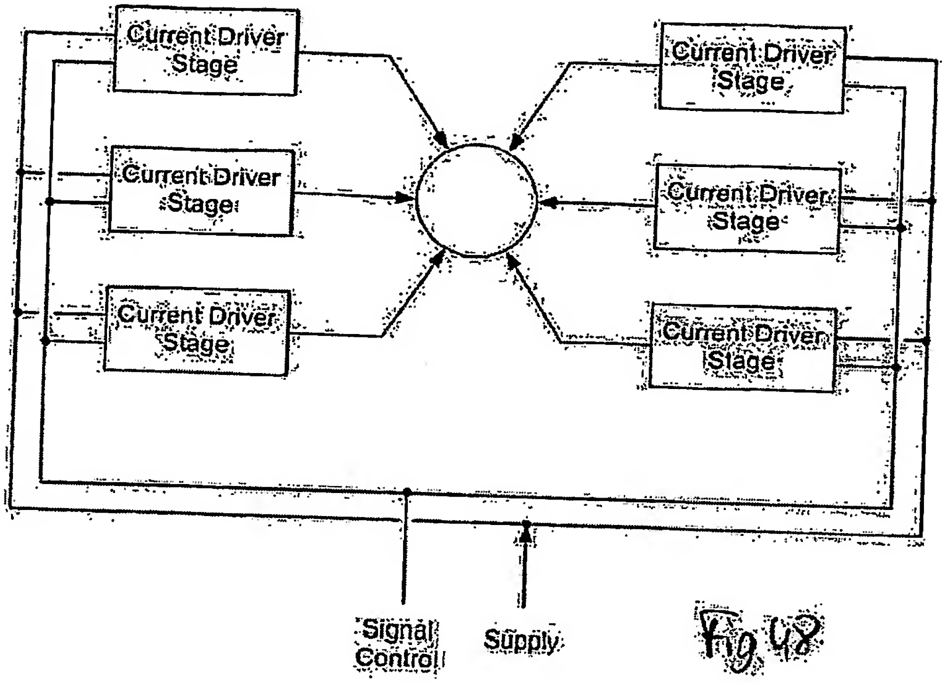

Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Signal Control
Supply

Fig 48

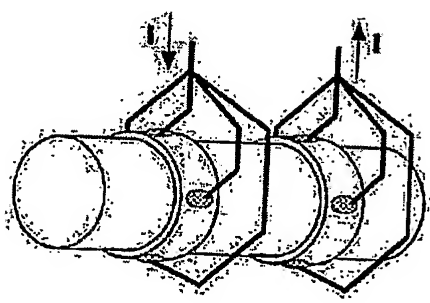

I
I

Fig 49

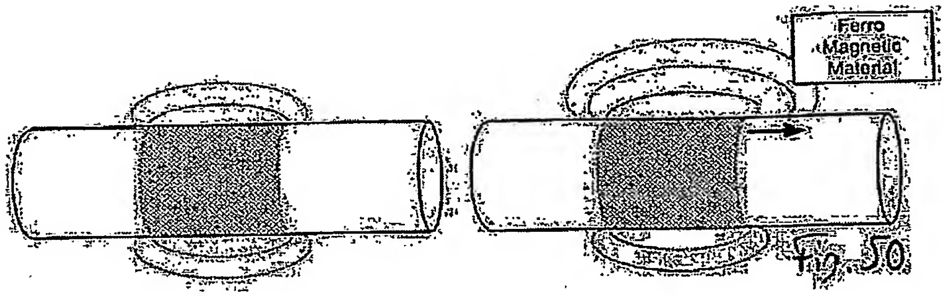


Fig. 50

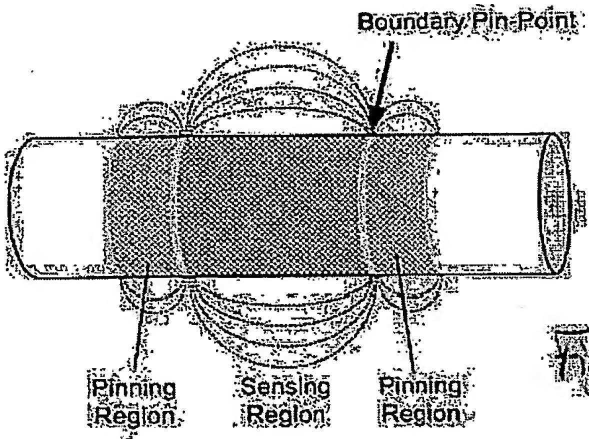


Fig. 51

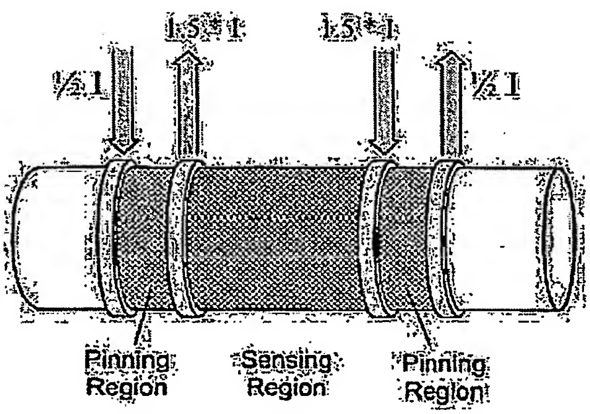


Fig. 52

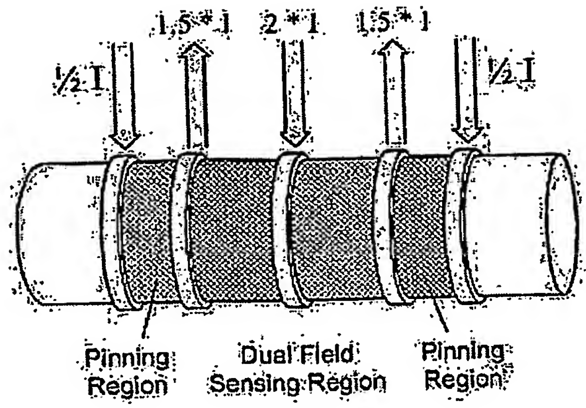


Fig 53

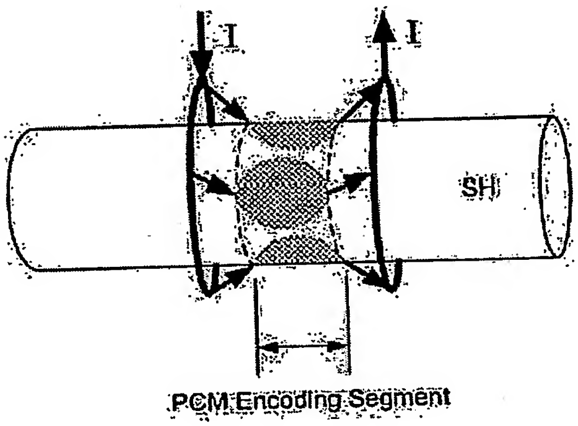


Fig 54

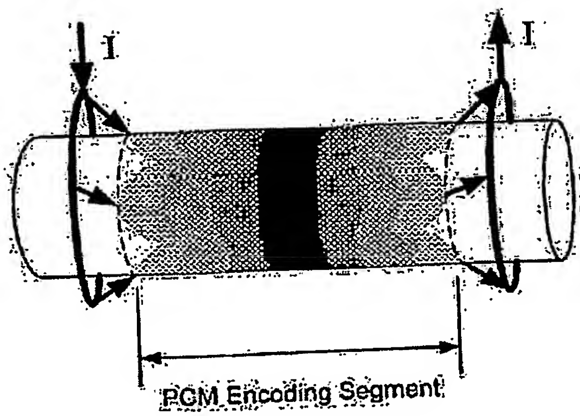


Fig 55

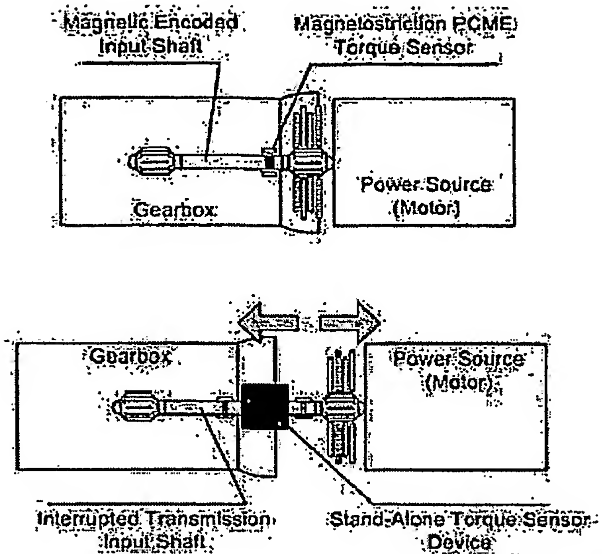

Magnetic Encoded Input Shaft
Magnetostriction PCME Torque Sensor
Gearbox
Power Source (Motor)
Gearbox
Power Source (Motor)
Interrupted Transmission Input Shaft
Stand-Alone Torque Sensor Device

Fig. 56

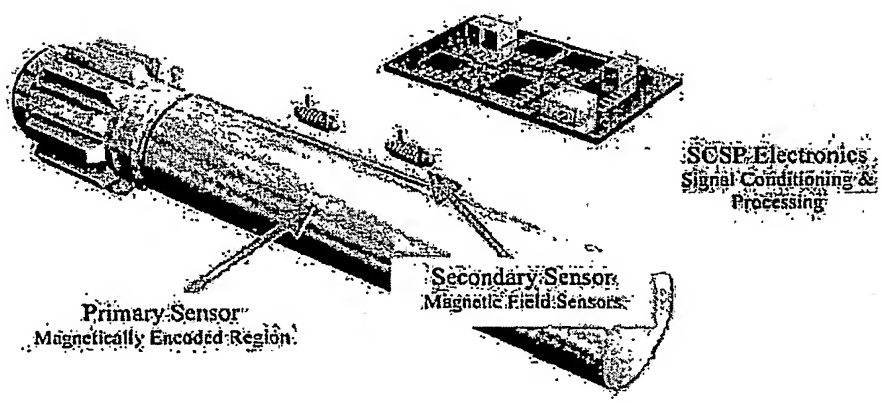

SCSP Electronics
Signal Conditioning & Processing
Secondary Sensor
Magnetic Field Sensors
Primary Sensor
Magnetically Encoded Region

Fig. 57

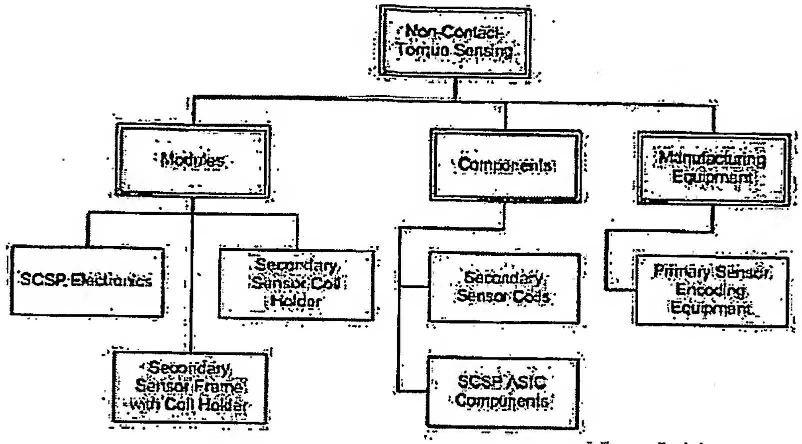


Fig 58

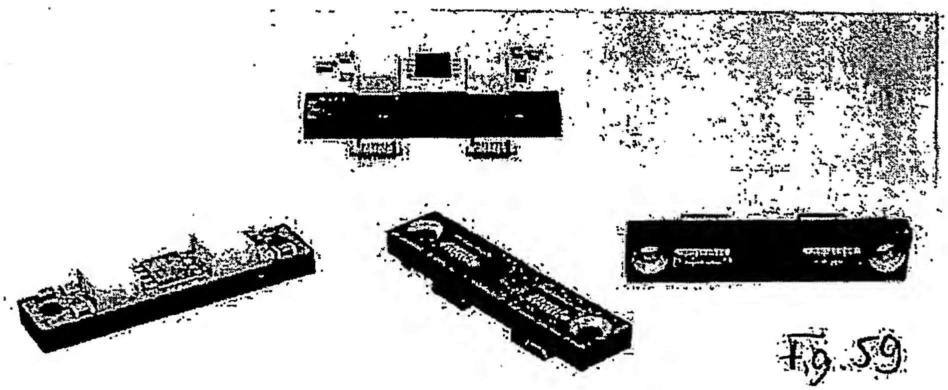


Fig 59

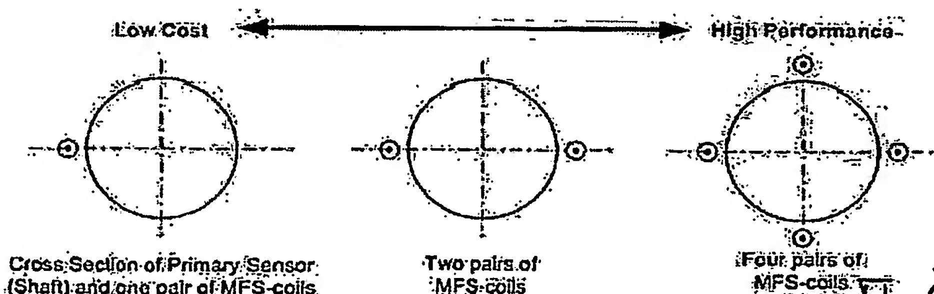


Fig 60

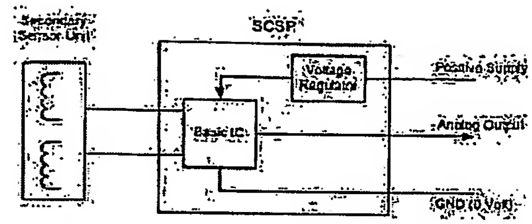

Secondary Sensor Unit
SCSP
Voltage Regulator
Positive Supply
Basic IC
Analog Output
GND (0 Volt)

Fig 61

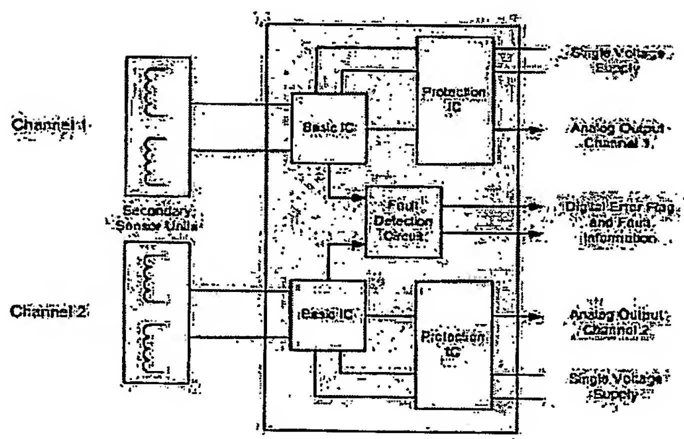

Single Voltage Supply
Protection IC
Channel 1
Basic IC
Analog Output Channel 1
Fault Detection Circuit
Digital Error Flag and Fault Information
Secondary Sensor Units
Channel 2
Basic IC
Analog Output Channel 2
Protection IC
Single Voltage Supply

Fig 62

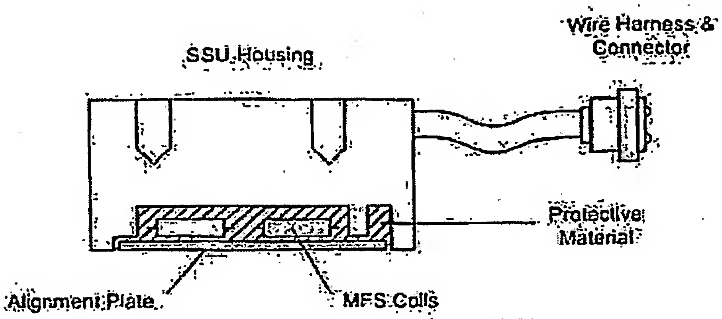

SSU Housing
Wire Harness & Connector
Protective Material
Alignment Plate
MFS Coils

Fig. 63

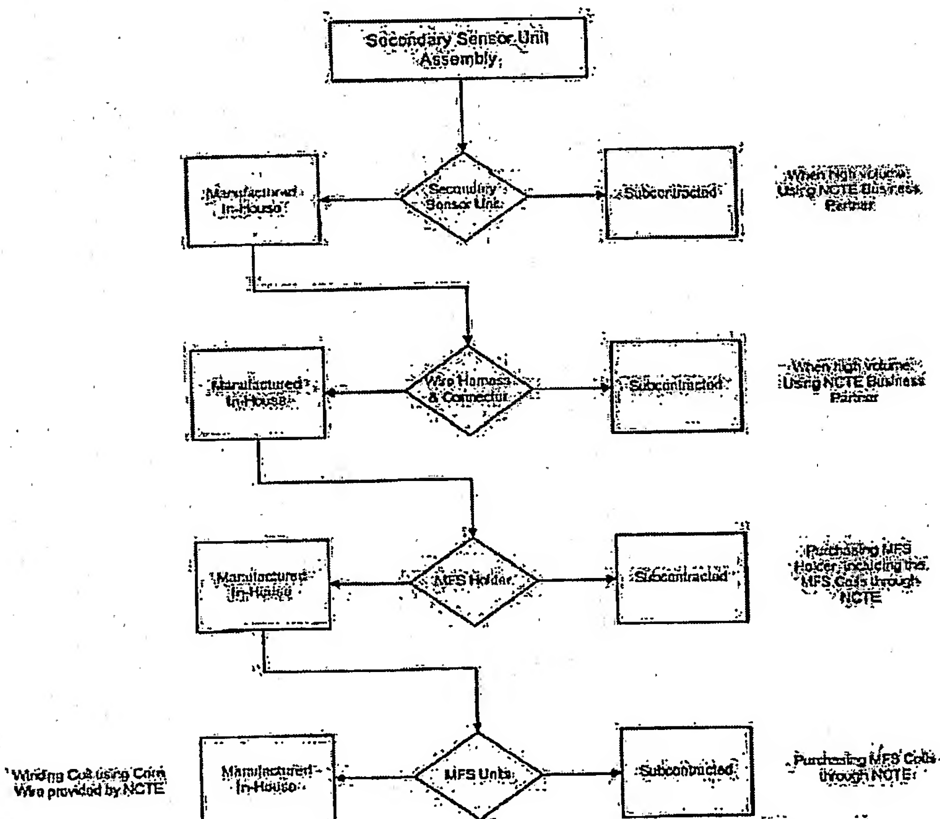

Secondary Sensor Unit Assembly
Manufactured In-House
Secondary Sensor Unit
Subcontracted
When high volume Using NCTE Business Partner
Manufactured In-House
Wire Harness & Connector
Subcontracted
When high volume Using NCTE Business Partner
Manufactured In-House
MFS Holder
Subcontracted
Purchasing MFS Holder, including the MFS Coils through NCTE
Winding Coil using Core Wire provided by NCTE
Manufactured In-House
MFS Units
Subcontracted
Purchasing MFS Coils through NCTE

Fig. 64

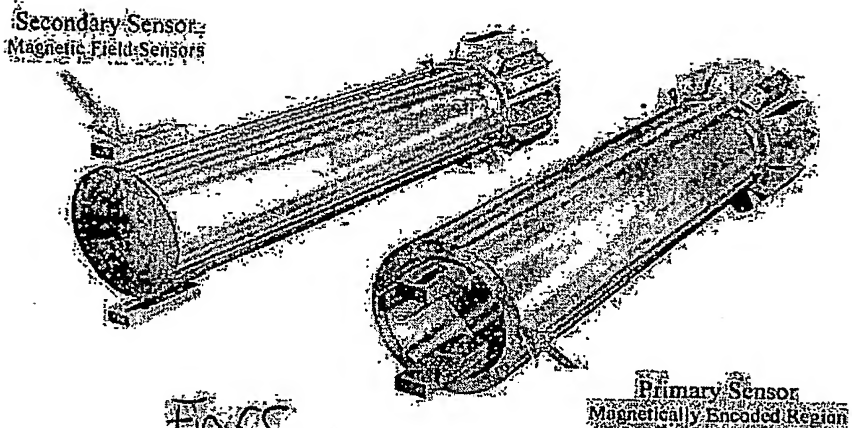

Secondary Sensor
Magnetic Field Sensors
Primary Sensor
Magnetically Encoded Region

Fig 65

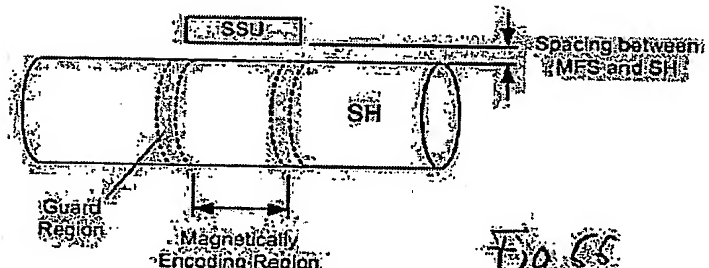

SSU
Spacing between MFS and SH
SH
Guard Region
Magnetically Encoding Region

Fig. 66

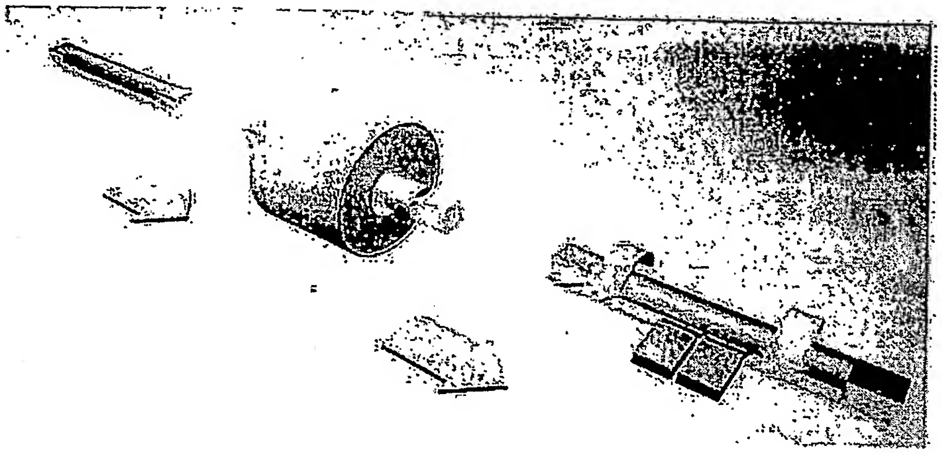


Fig. 67

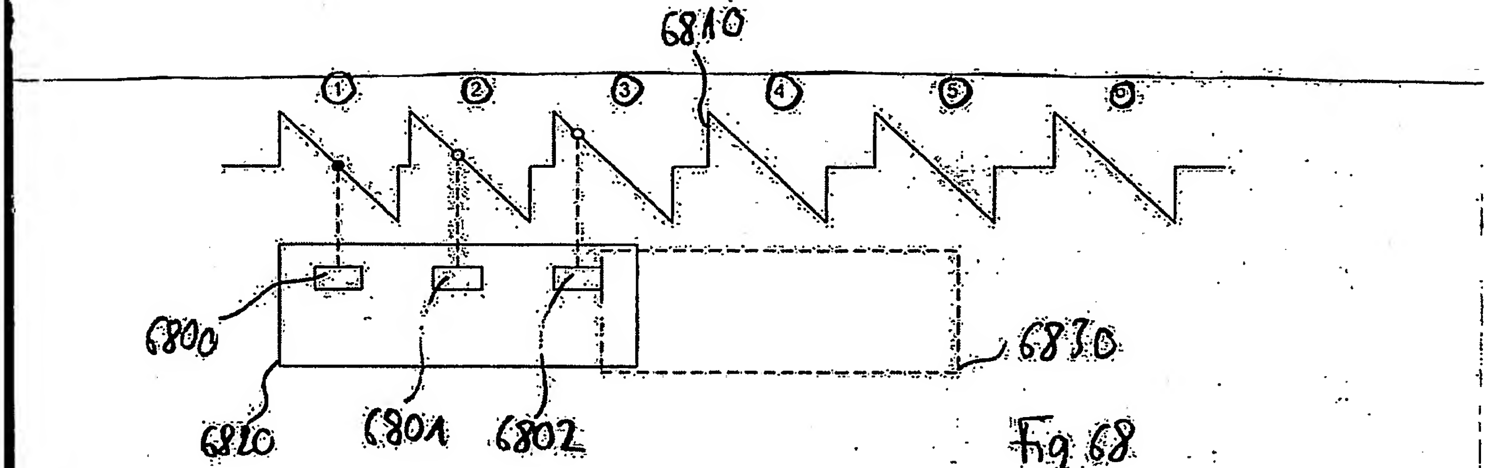


Fig 68

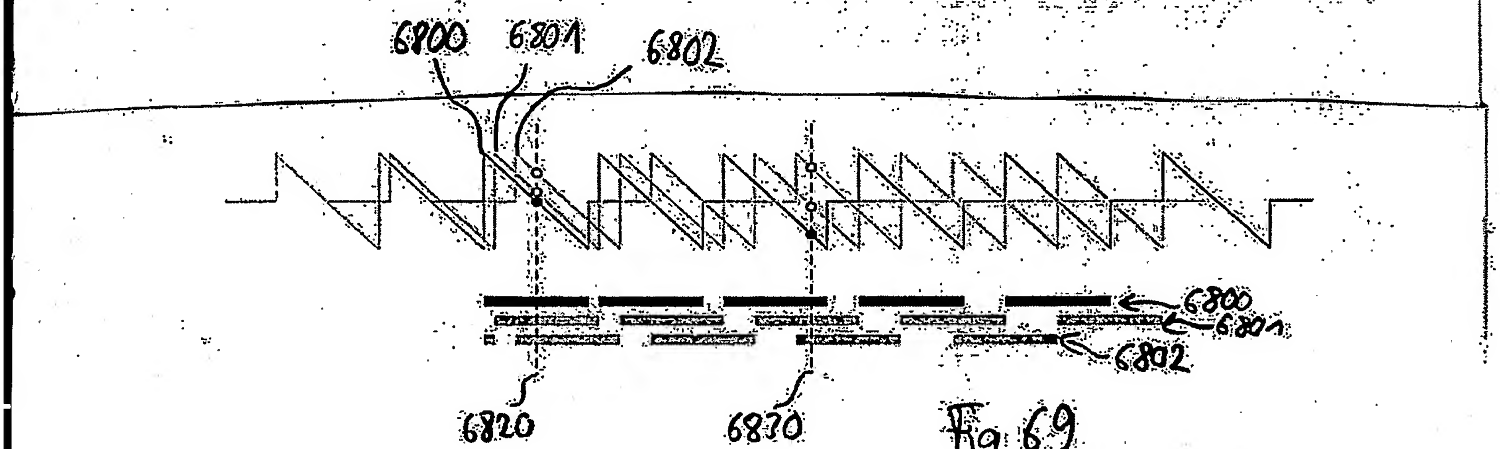


Fig 69

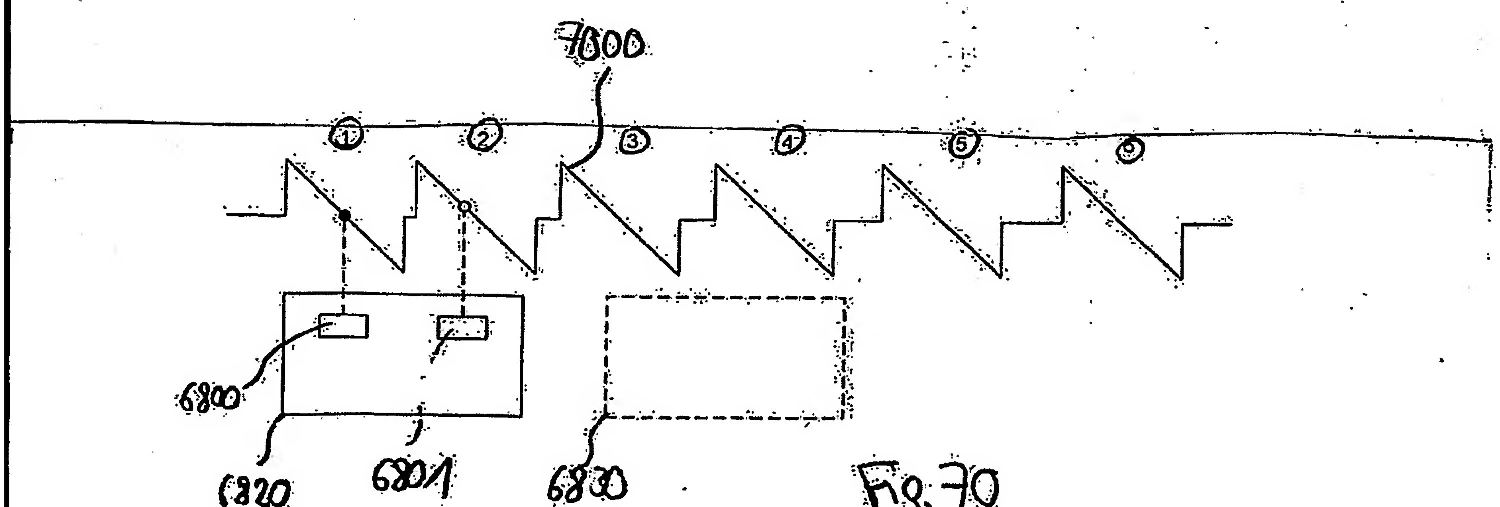


Fig. 70

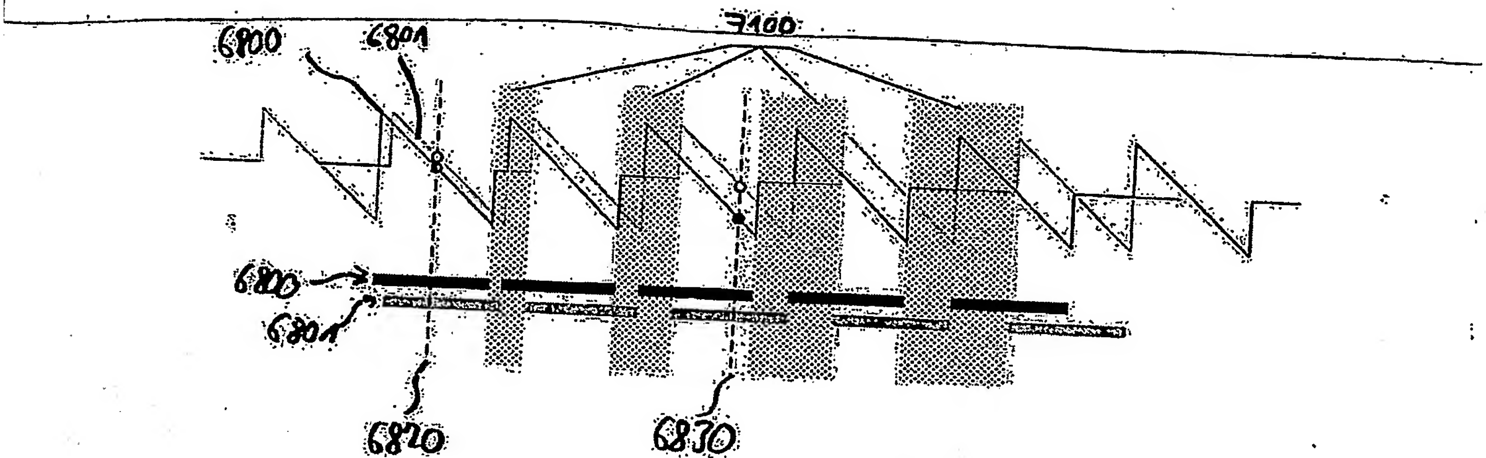


Fig 71

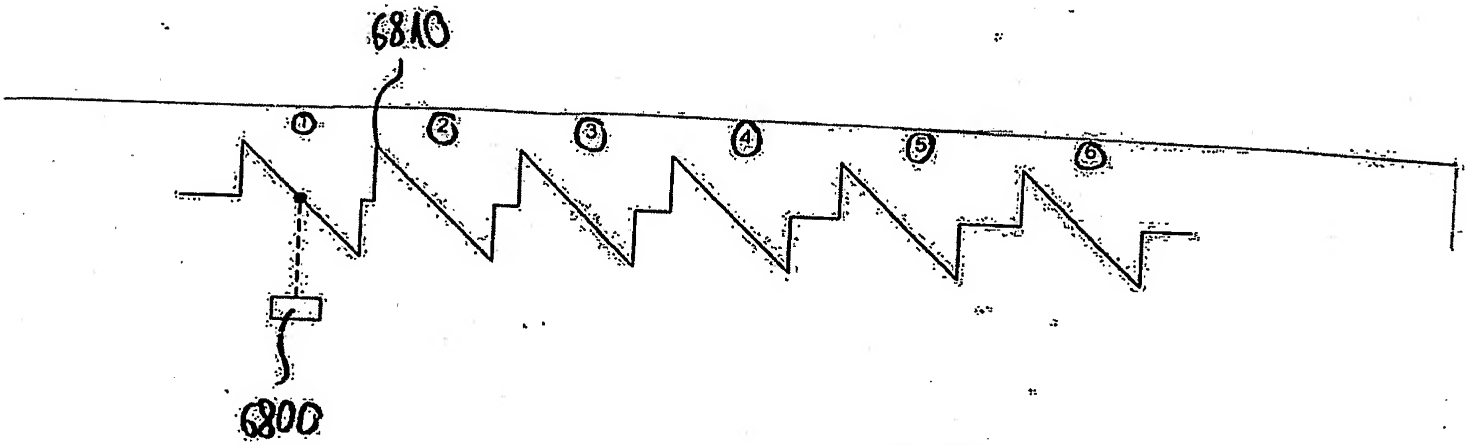


Fig 72

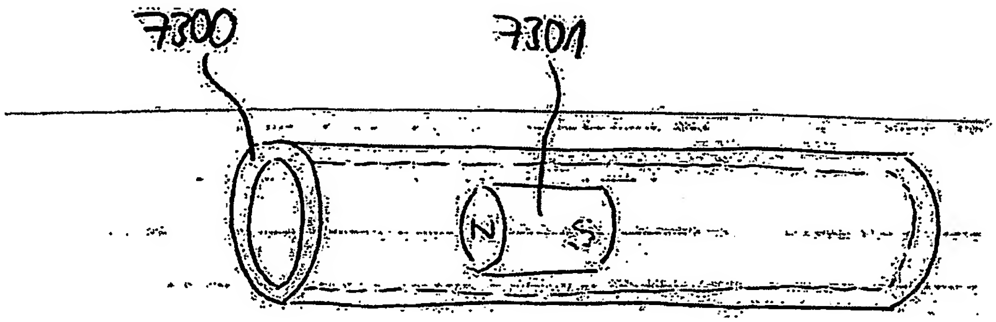


Fig. 73

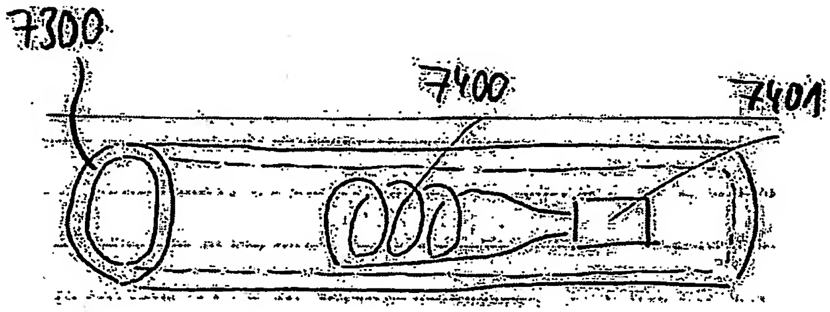


Fig. 74

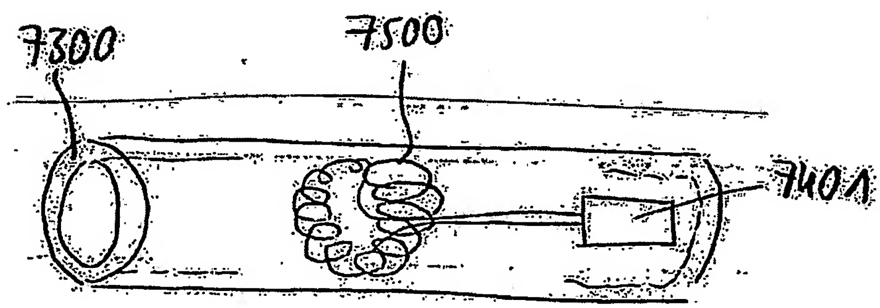


Fig. 75

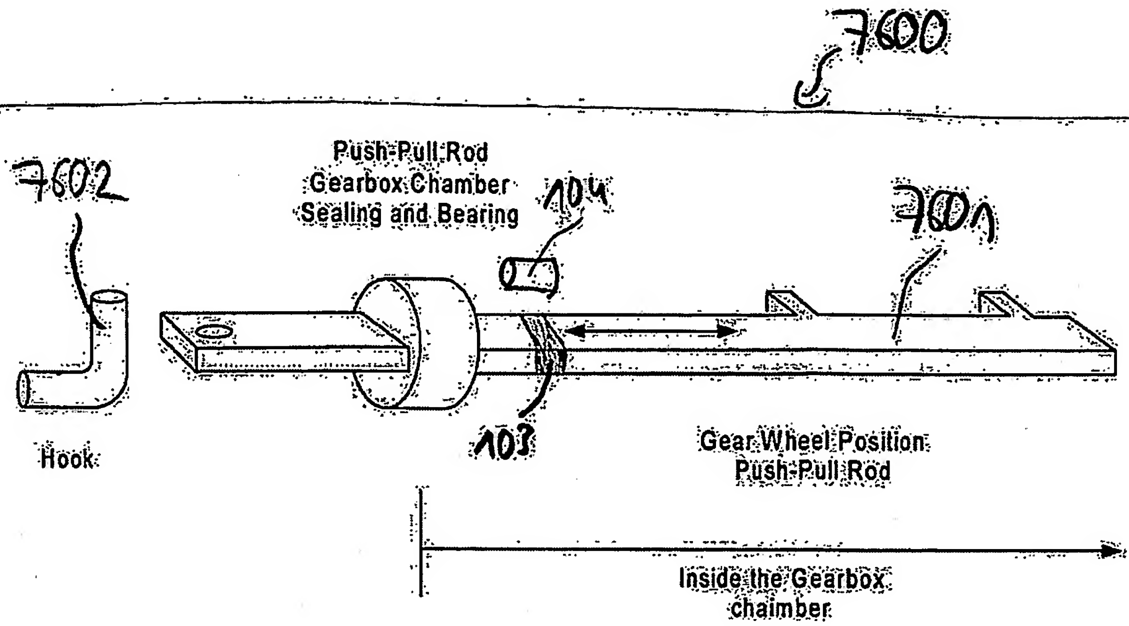

7600
7602
Push-Pull Rod
Gearbox Chamber
Sealing and Bearing
104
7601
Hook
103
Gear Wheel Position
Push-Pull Rod
Inside the Gearbox
chaimber

Fig.76

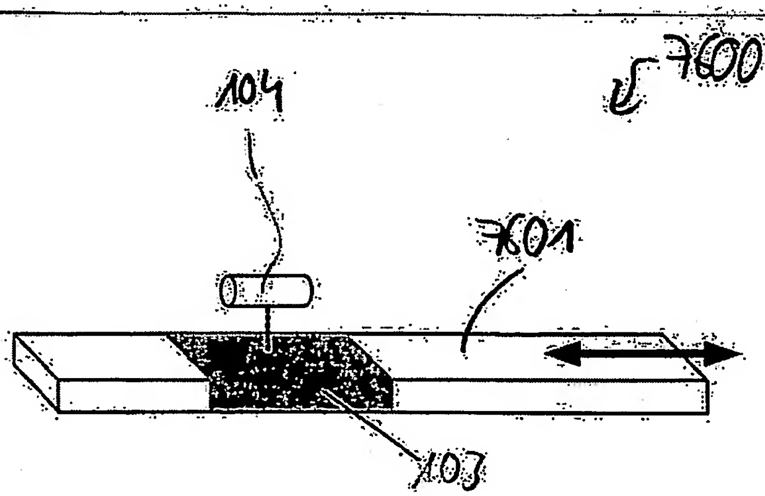

7600
104
7601
103

Fig.77